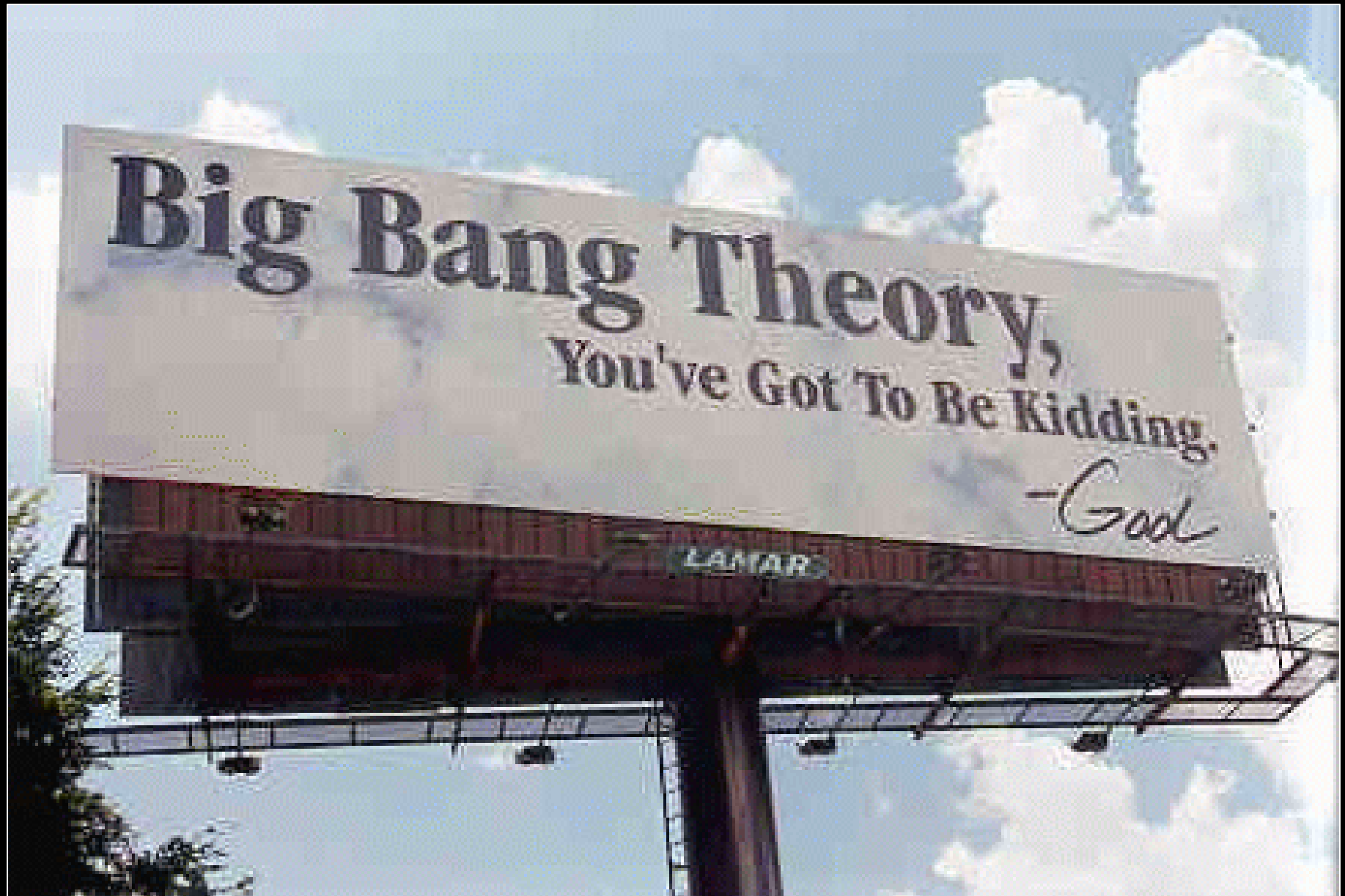




Models Lecture 9

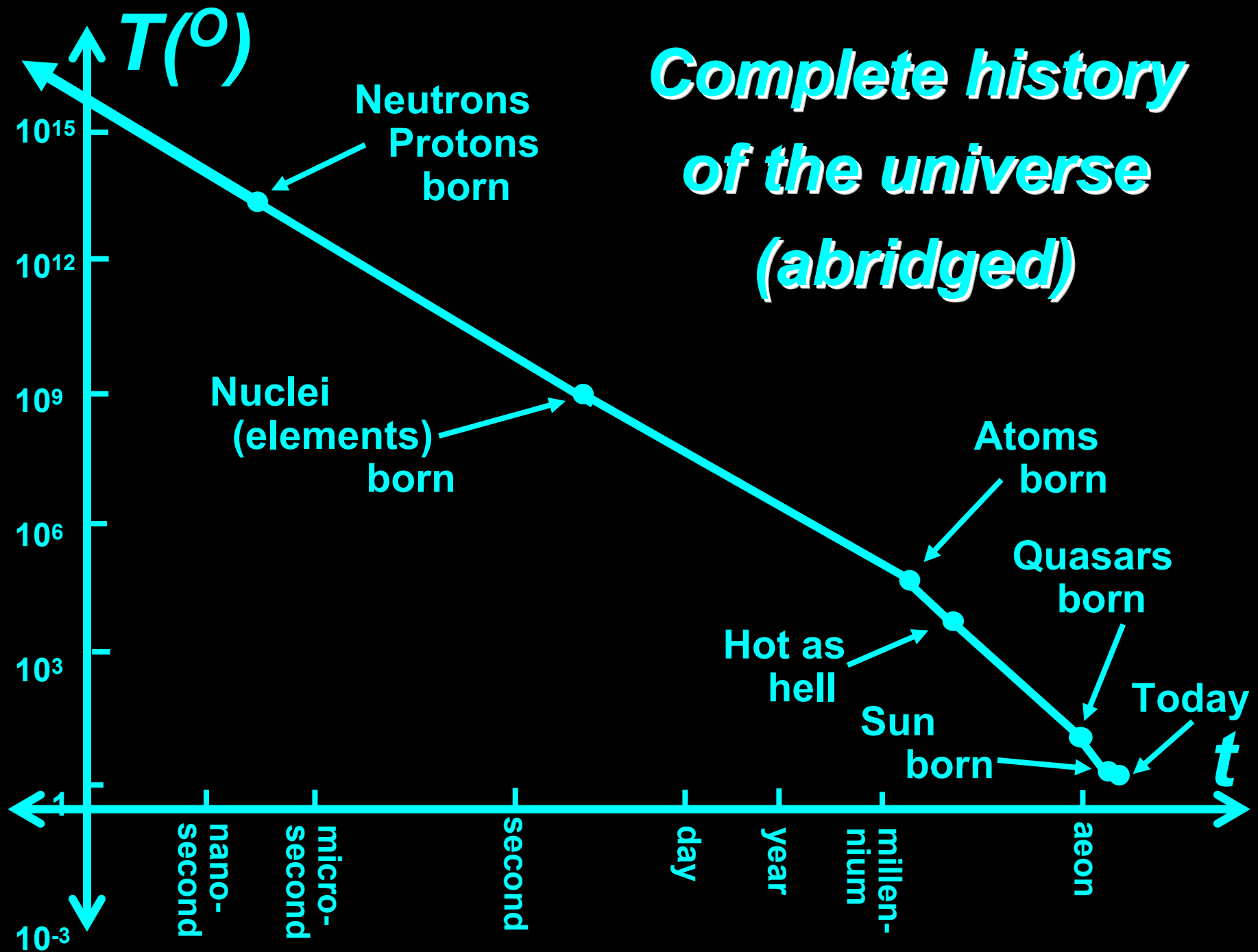
The Big Bang

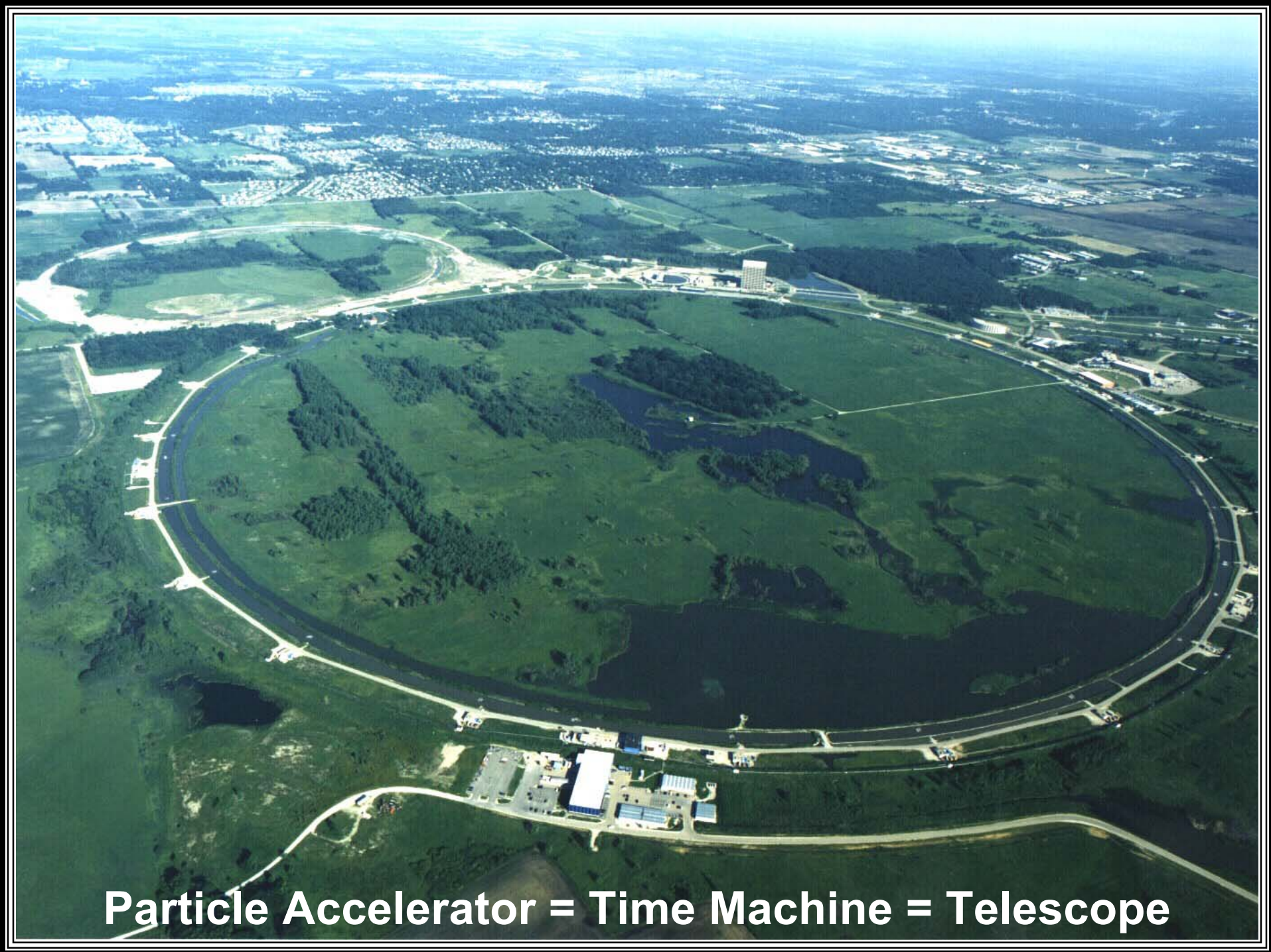


Cosmological Weather Report

- Today $T=3K$
- Yesterday was hotter!
- Tomorrow will be colder!

Complete history of the universe (abridged)





Particle Accelerator = Time Machine = Telescope



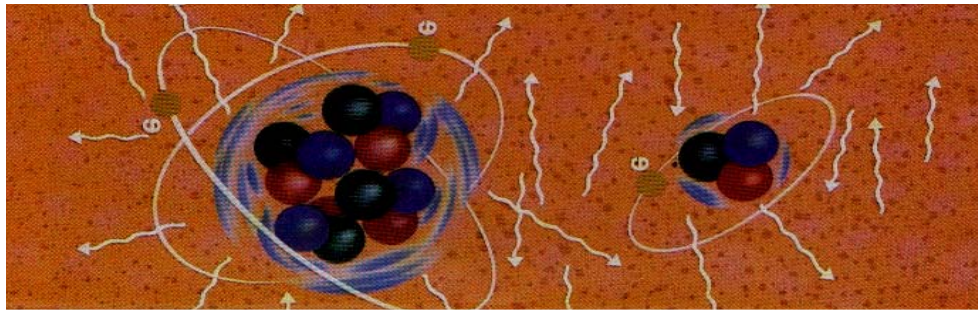
Fermilab's



Primordial

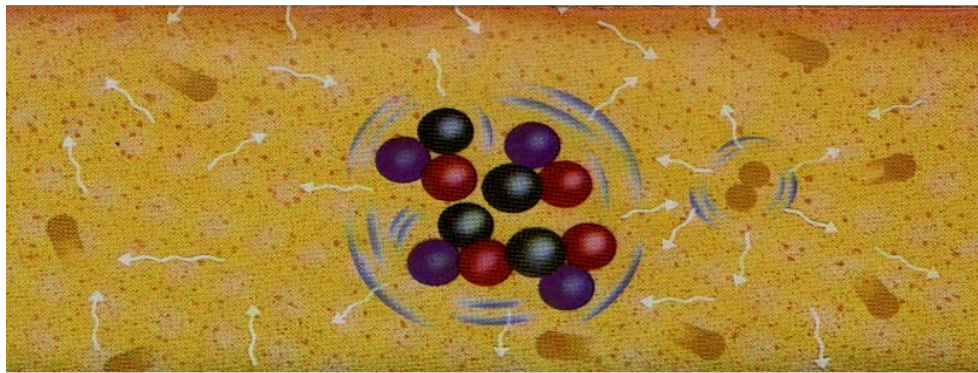
SOUP

**380,000
years**



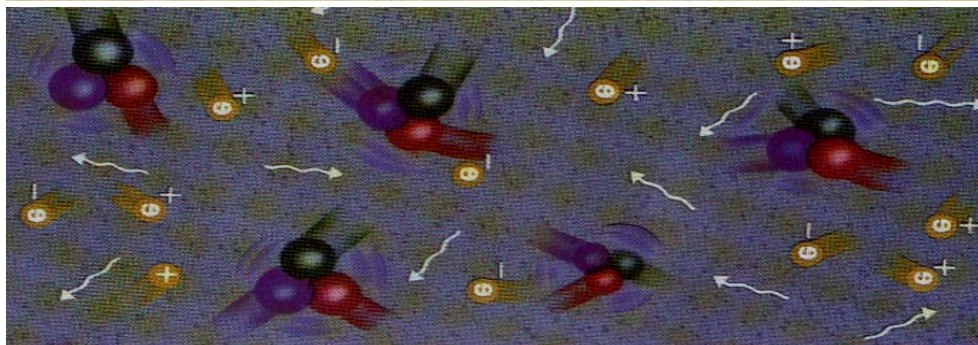
**atoms
form**

**3
minutes**



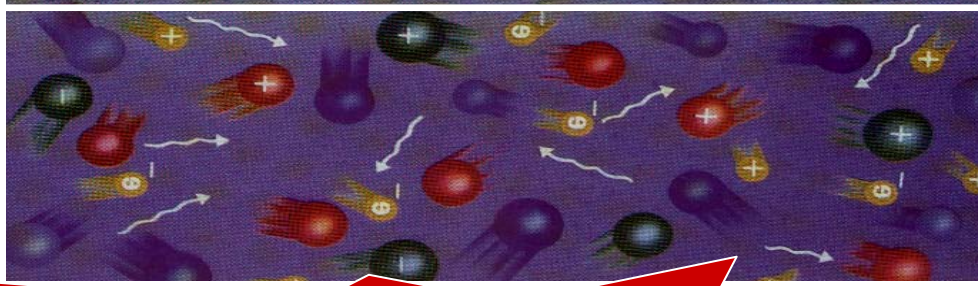
**nuclei
form**

**1-micro
second**



**neutrons
protons
form**

**4-pico
seconds**



**primordial
soup**

BANG!

Periodic table - chemist

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Periodic table - cosmologist

H

He

Metals

The Universe today:

73%	Hydrogen	(10^{-5} ^2H -deuterium)
26%	Helium	(10^{-5} ^3He)
1%	Metals	

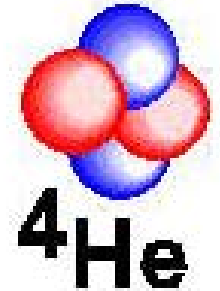
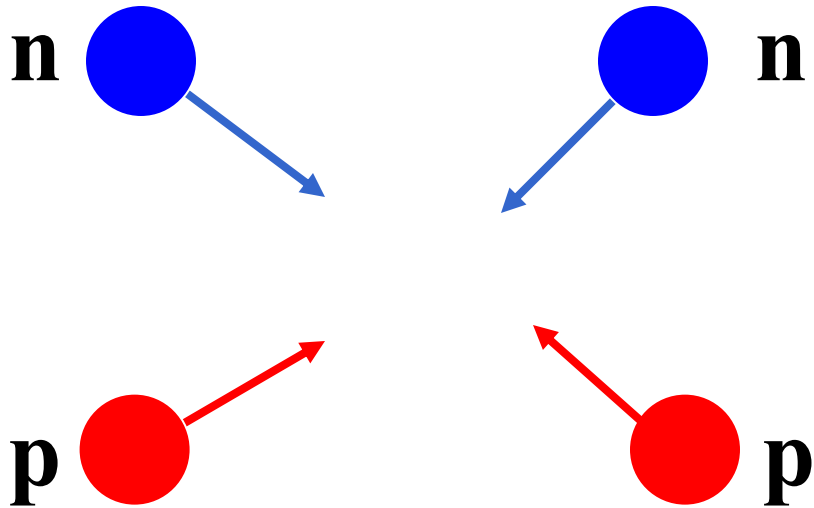
The Universe 3 minutes AB:

76%	Hydrogen	(10^{-5} ^2H -deuterium)
24%	Helium	(10^{-5} ^3He)
$10^{-8}\%$	Lithium	

Nucleosynthesis

...the process of assembling nuclei either by nuclear fusion or nuclear fission.

Nuclear Alchemy



nucleus	mass (AMU)	sum (AMU)
---------	------------	-----------

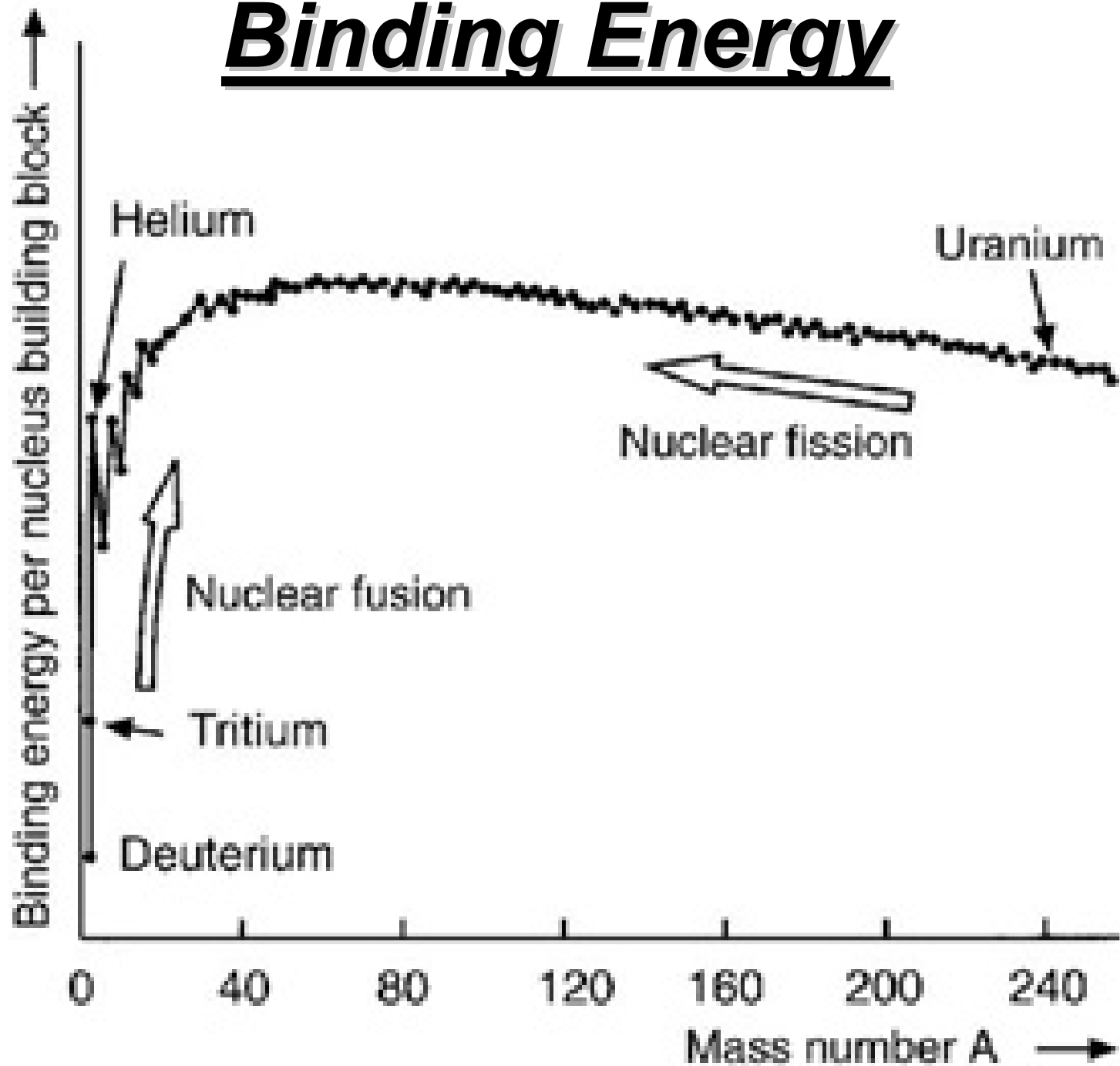
p	1.0073	4.0320
p	1.0073	
n	1.0087	
n	1.0087	

$$m_{4He} < 2m_p + 2m_n$$

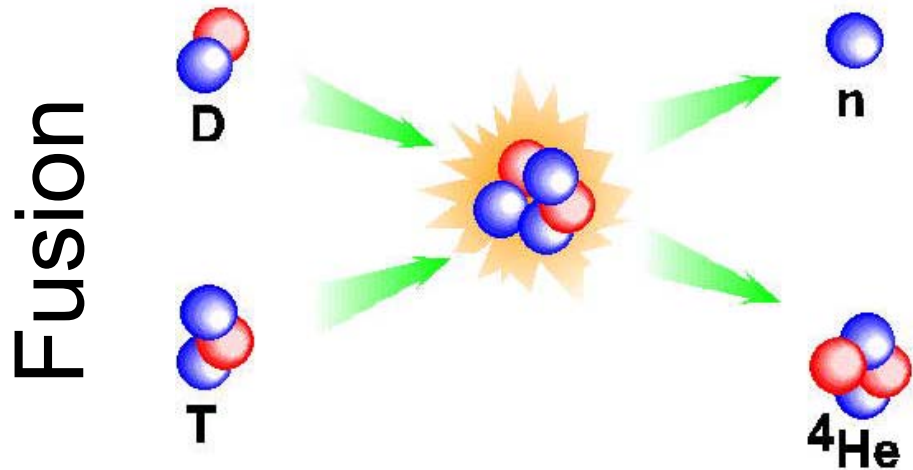
Difference in mass (Binding Energy) released as energy
à la $E = Mc^2$

4He	4.0026
------------	--------

Binding Energy



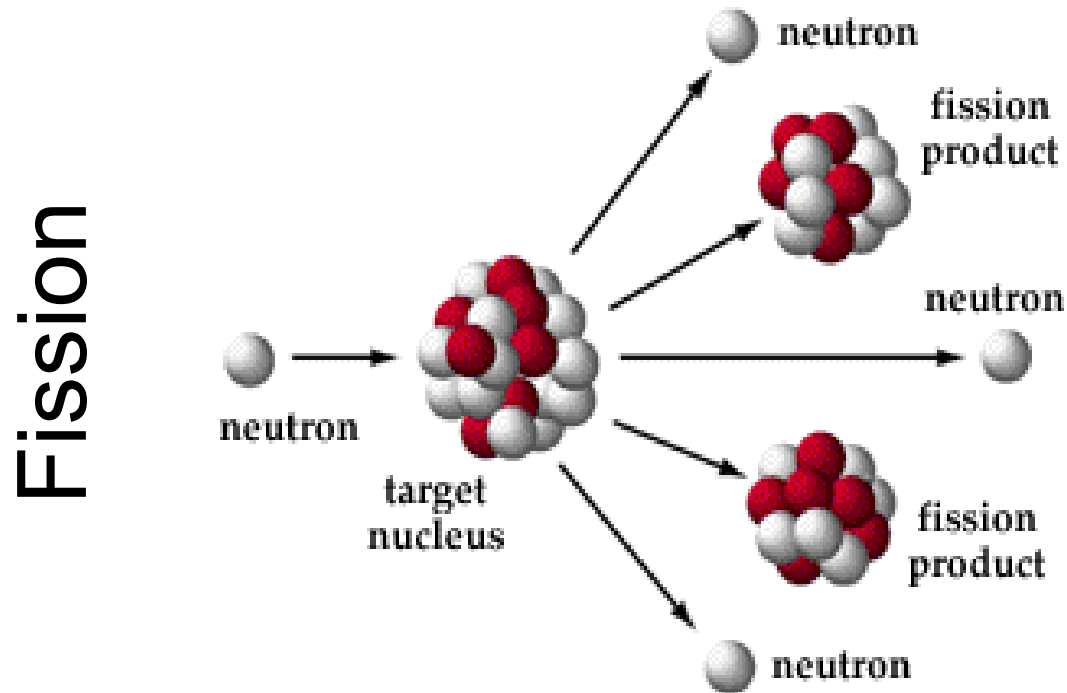
Binding Energy



nucleus	mass (AMU)	sum (AMU)	difference (AMU)
D	2.0141	5.0301	0.0188
T	3.0160		
n	1.0087	5.0113	
⁴ He	4.0026		

Difference in mass released as energy à la $E = Mc^2$

Nuclear Alchemy



$$m_n + m_{\text{TARGET}} > m_{\text{PRODUCTS}}$$

Difference in mass released as energy à la $E = Mc^2$

Nucleosynthesis

...the process of assembling nuclei either by nuclear fusion or nuclear fission.

Big Bang nucleosynthesis (BBN): within the first three minutes of the universe and is responsible for most of the deuterium, helium-4, helium-3, and lithium-7. No elements heavier than lithium could be formed.

Stellar nucleosynthesis: creates most of the heavier elements between lithium and iron.

Supernova nucleosynthesis: produces most of the elements heavier than iron.

Cosmic ray spallation: produces some light elements like lithium and boron.

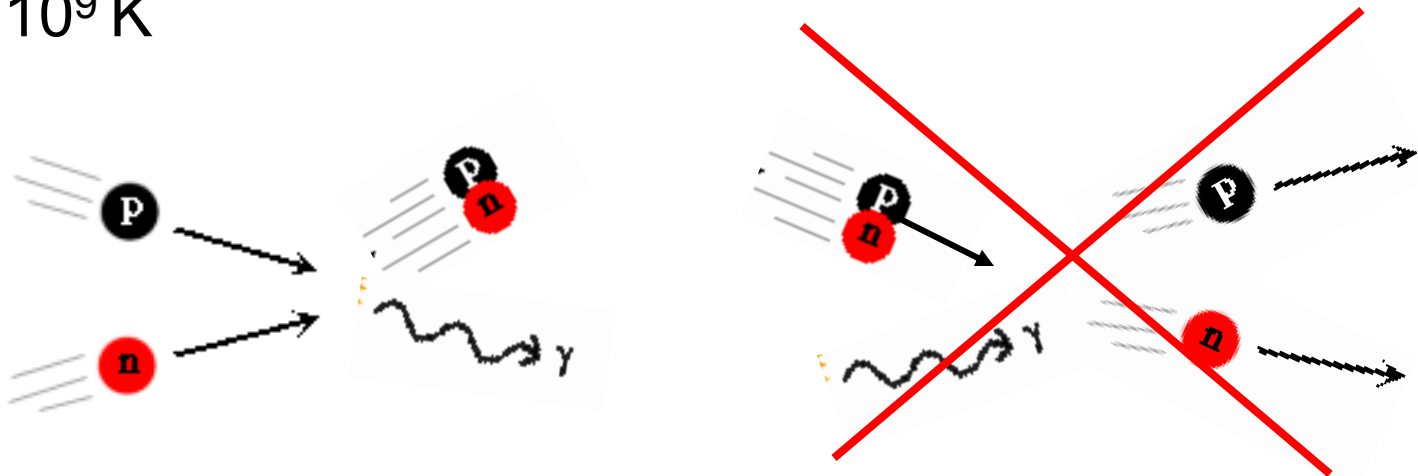
Big Bang Nucleosynthesis

1. $T \gg 10^{10} \text{ K}$



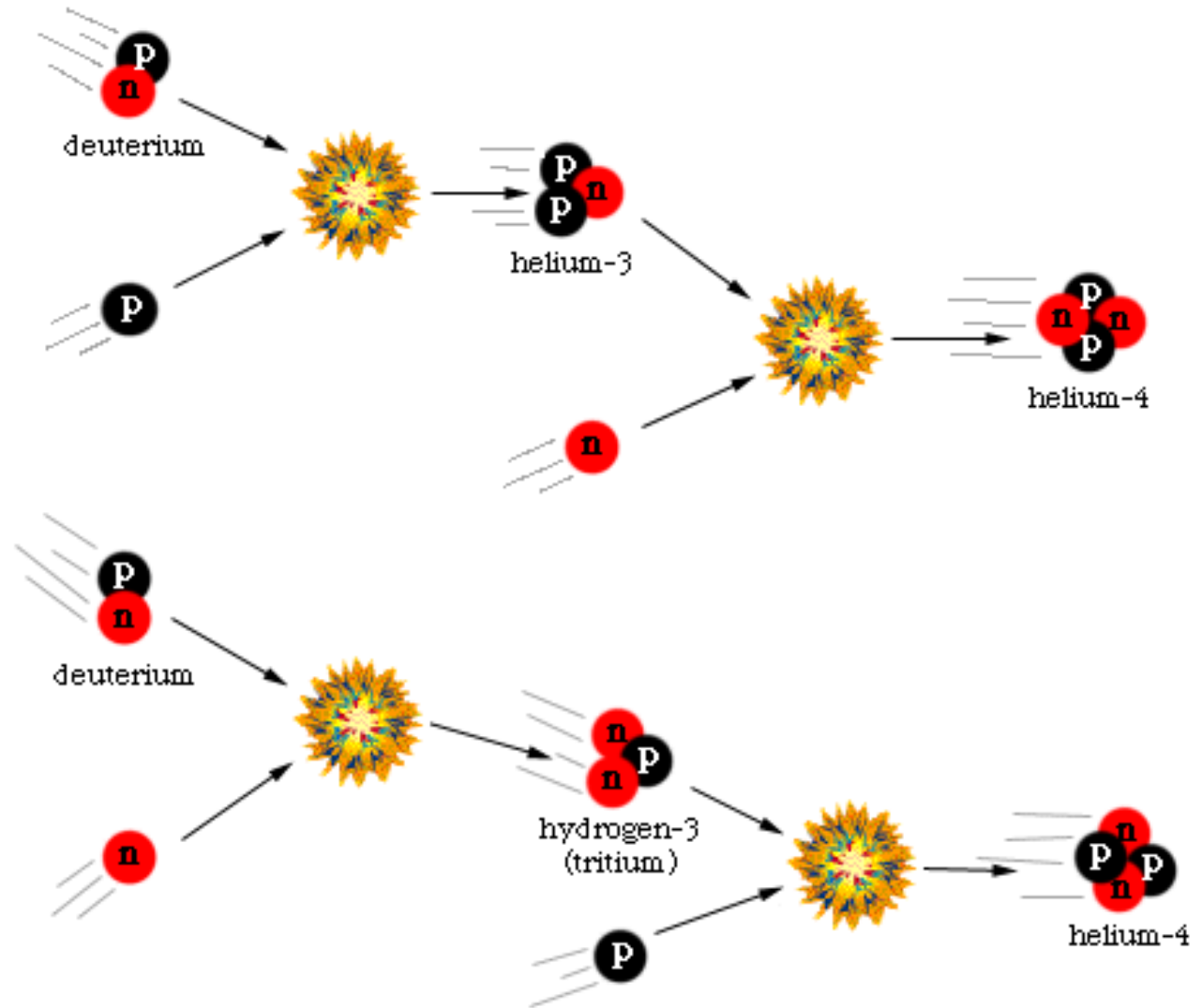
(Deuterium has a low binding energy)

2. $T \approx 10^9 \text{ K}$



Big Bang Nucleosynthesis

3. $T \lesssim 10^9 \text{ K}$

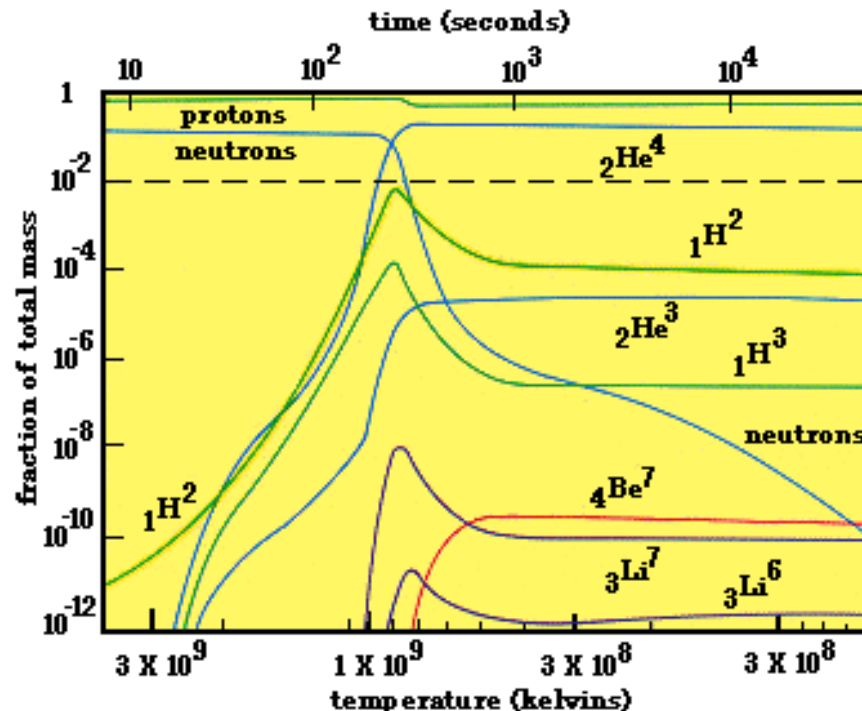


(Helium-4 has a high binding energy)

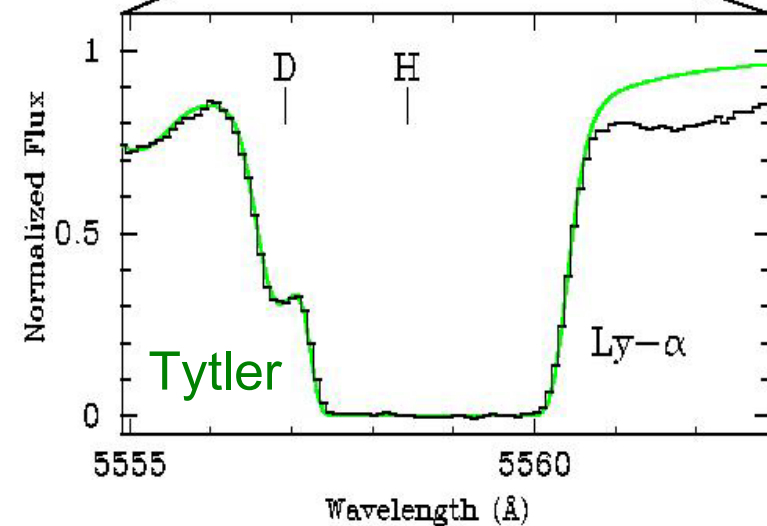
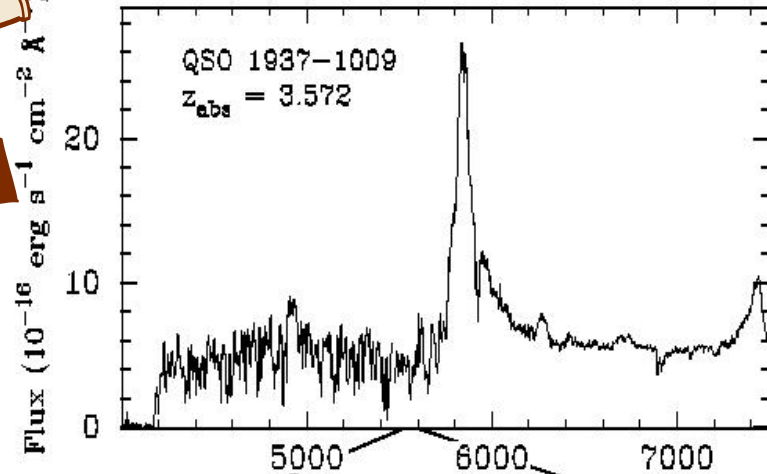
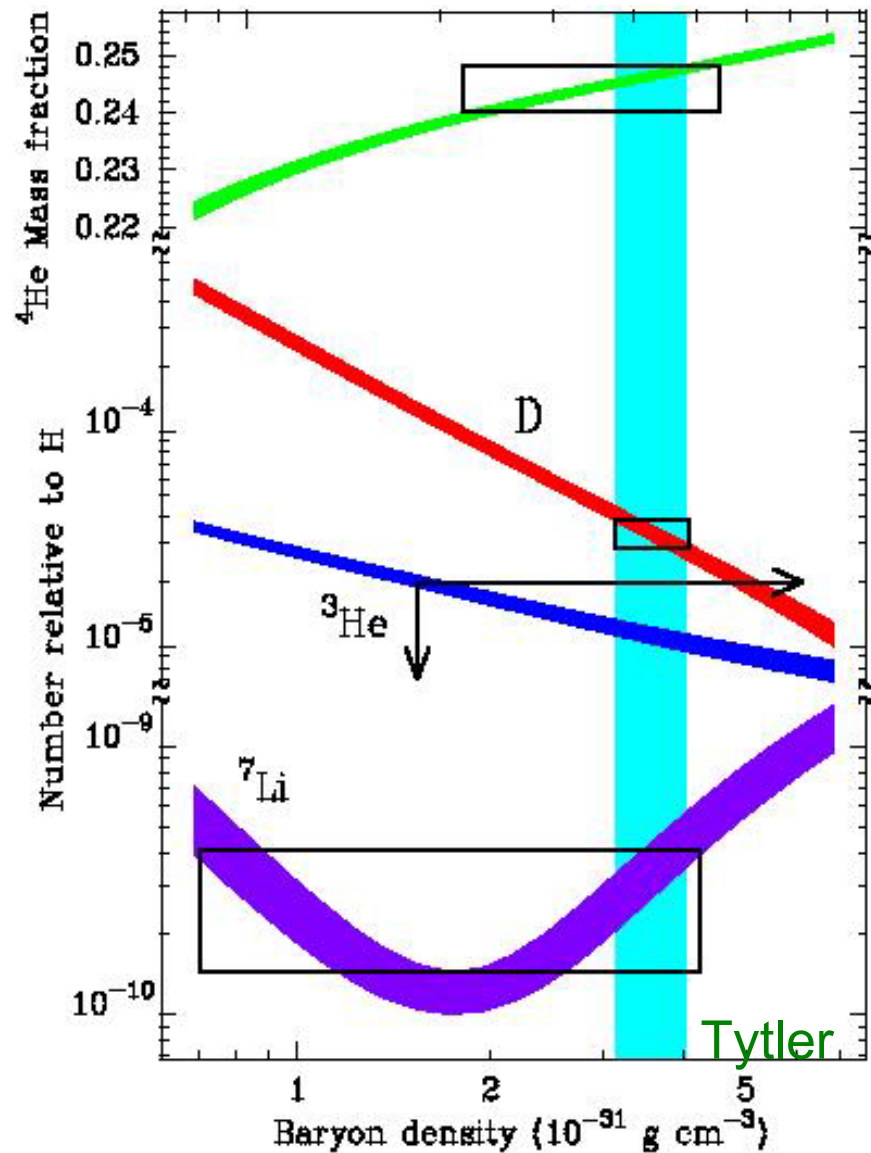
Big Bang Nucleosynthesis

4. $T \lll 10^9 \text{ K}$

- neutrons decay or absorbed into helium
- universe consists mostly of protons and helium
- $p + \text{helium} \rightarrow$ (no stable element with $A=5$)
- $\text{helium} + \text{helium} \rightarrow$ (no stable element with $A=8$)
- temperature too low for nucleosynthesis

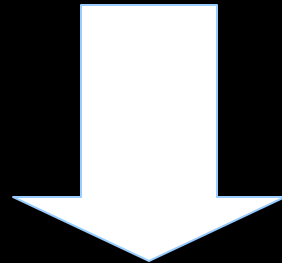


Big Bang Nucleosynthesis



The Universe 3 minutes AB:

Big bang (rate of change of the temperature)
Nuclear physics (binding energies, reactions)

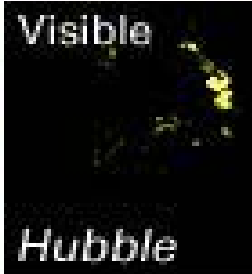
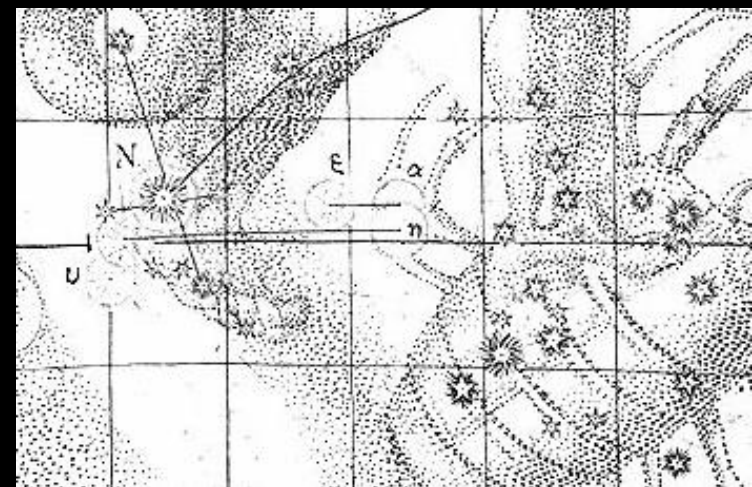


76%	Hydrogen	(10^{-5} ^2H -deuterium)
24%	Helium	(10^{-5} ^3He)
$10^{-8}\%$	Lithium	

Kepler's supernova



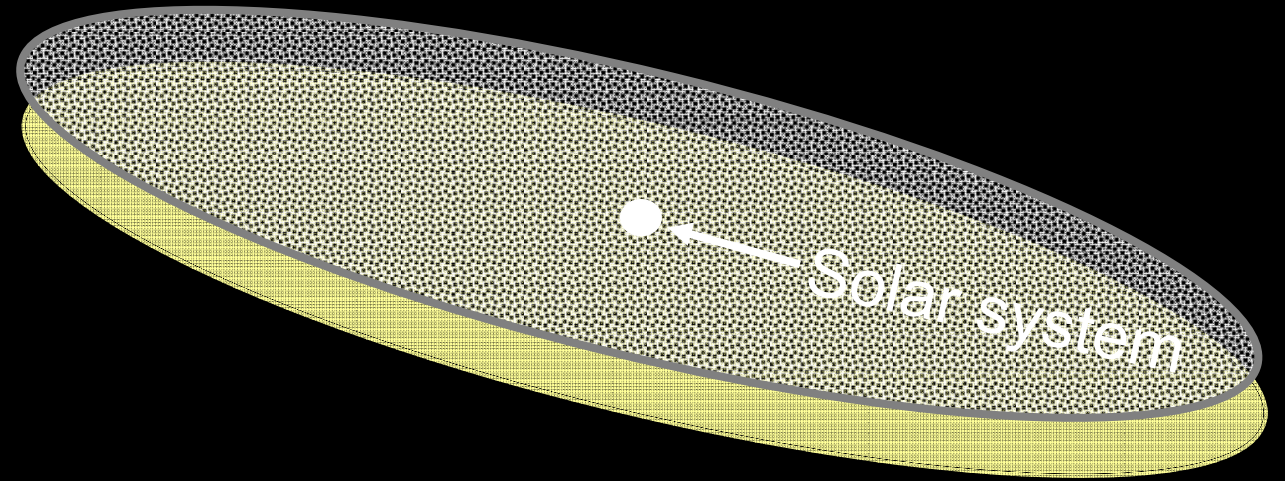
Observed 1604
in Ophiuchus
Peak magnitude = -2.25
Distance < 10 kpc



Cosmology 100 Years Ago

- 1) Nature of space and time: absolute
- 2) Origin of the Universe: not an astronomy issue
- 3) Evolution of the Universe: stationary
- 4) Arrangement of the Universe:

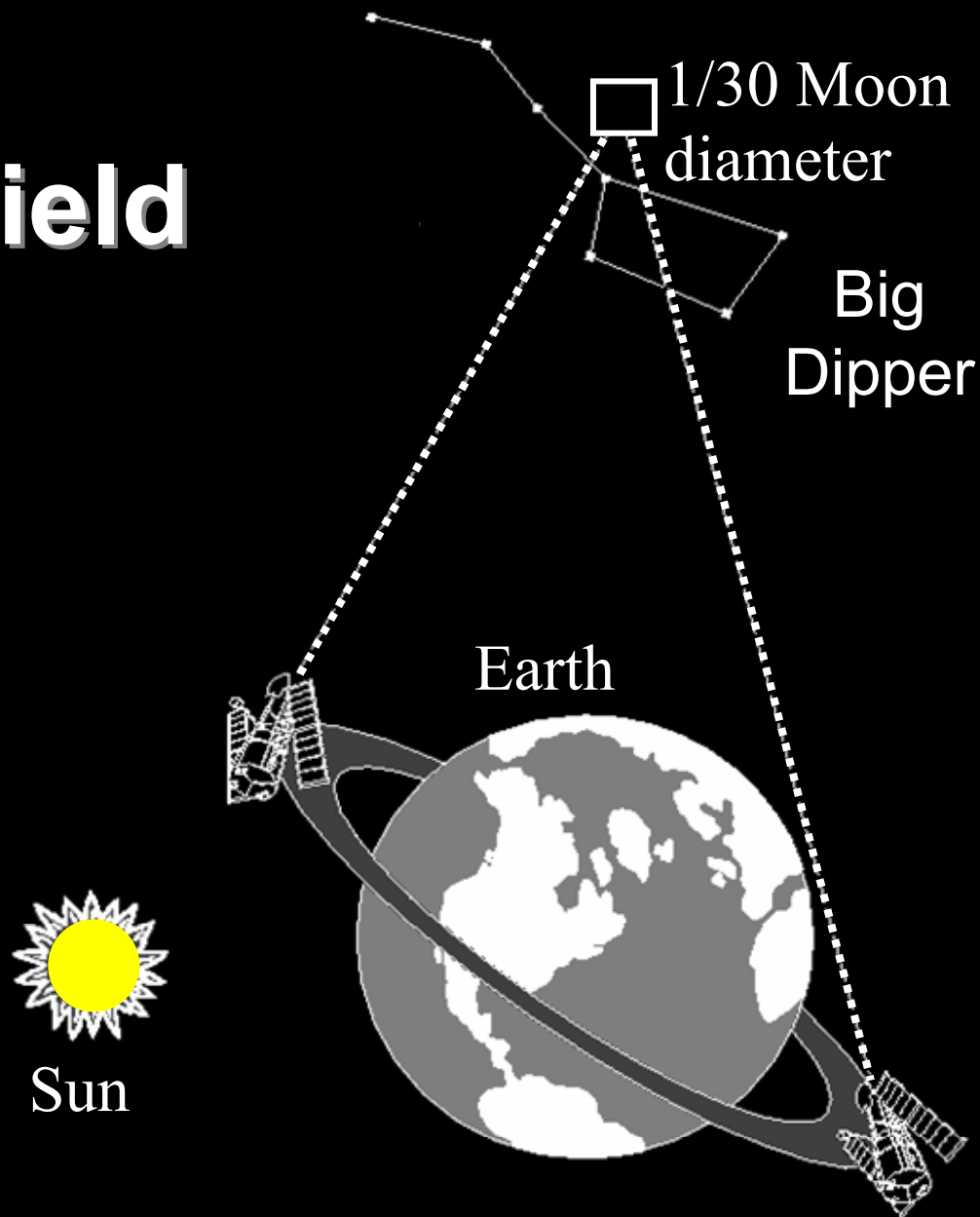
6,500
light years I



30,000 light years

- 5) Composition of the Universe: starz' in the hood

Hubble Deep Field

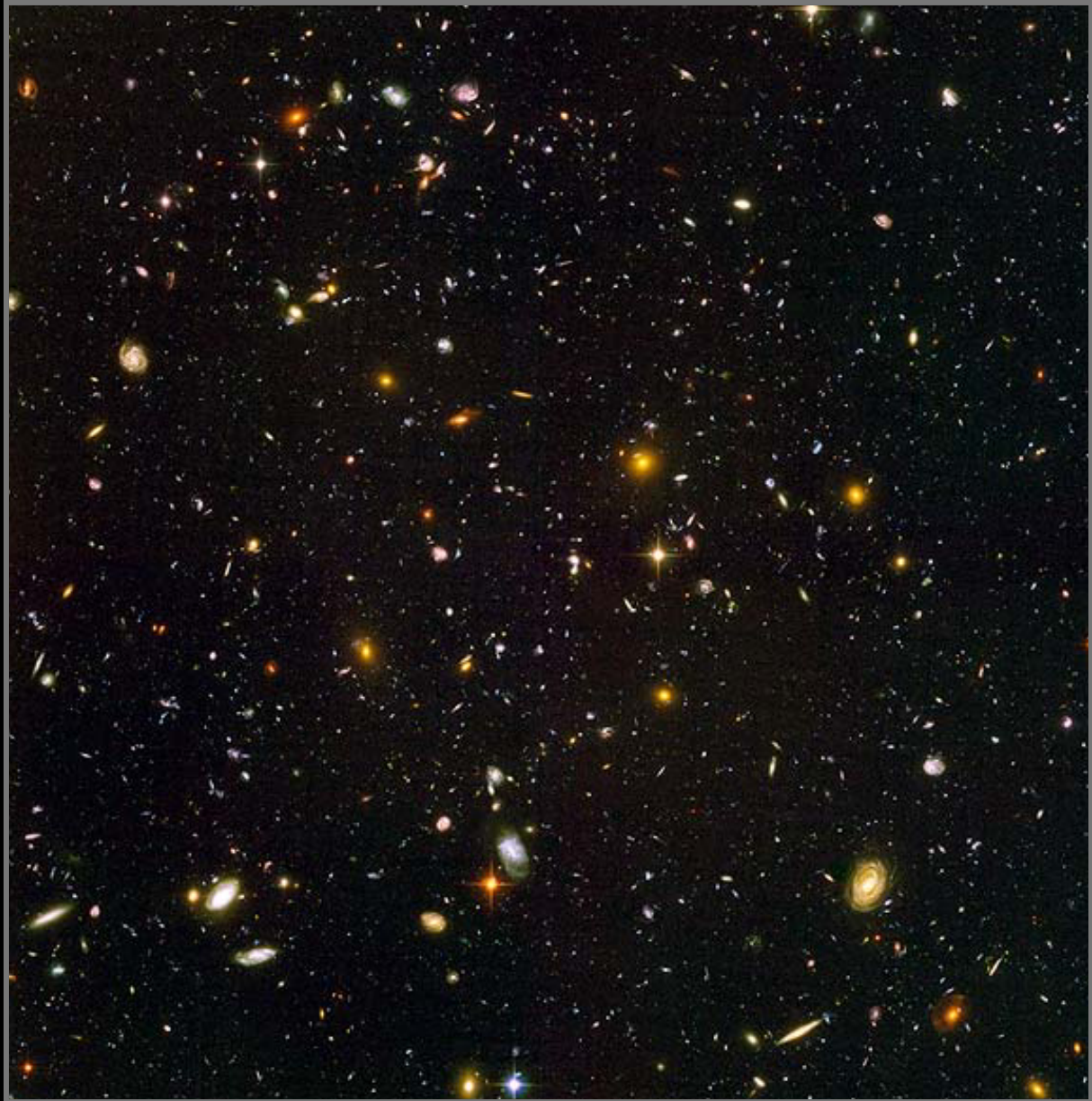


The Hubble Ultra Deep Field

UNIVERSE
OF
GALAXIES

3000
here →

50 billion
over entire
sky



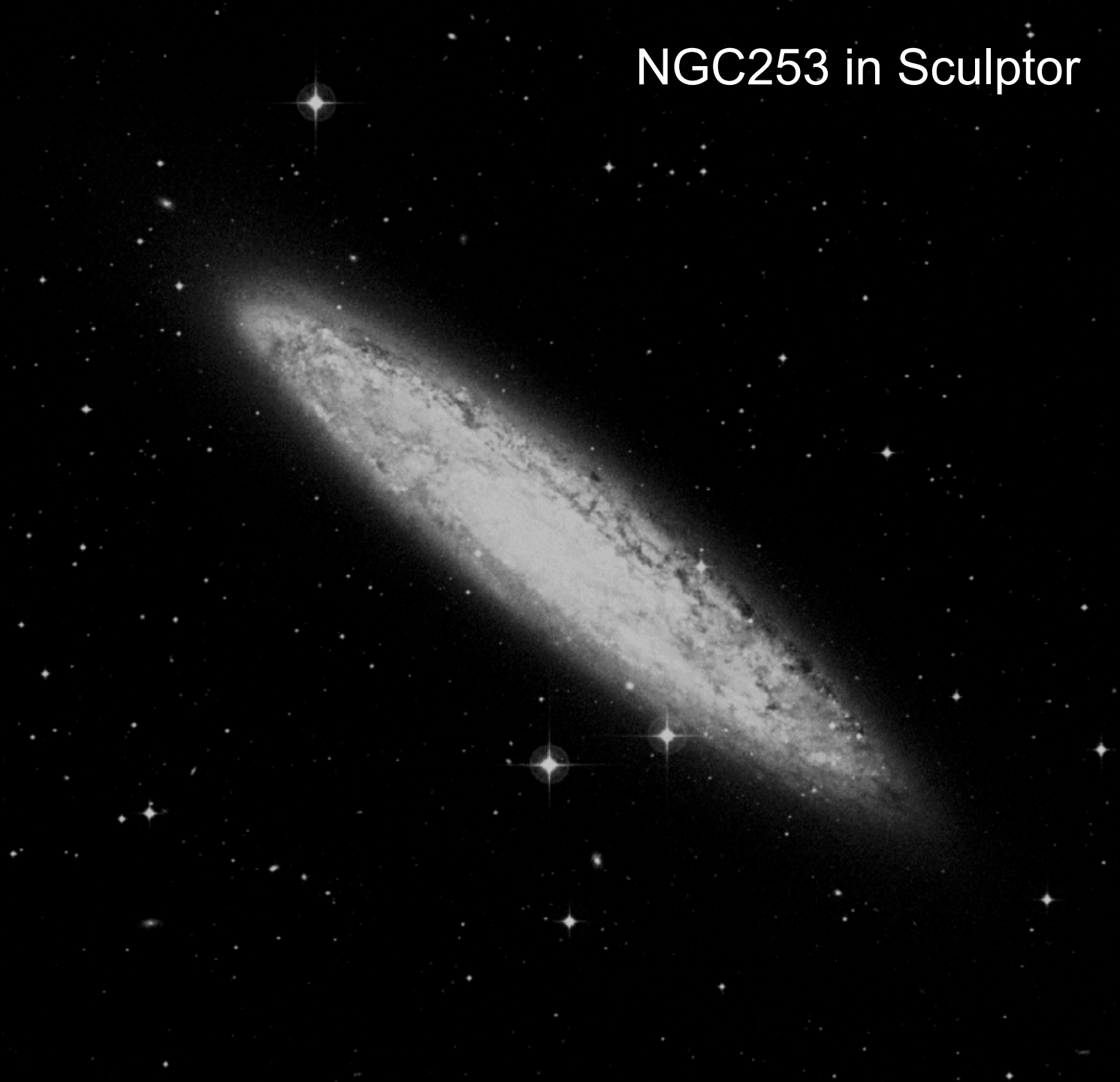
The Visible Universe

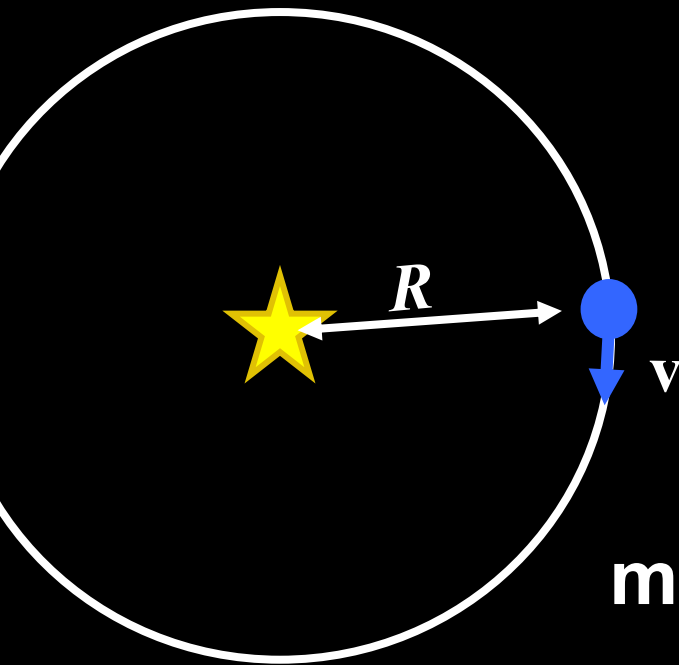


Spitzer Space Telescope

M81

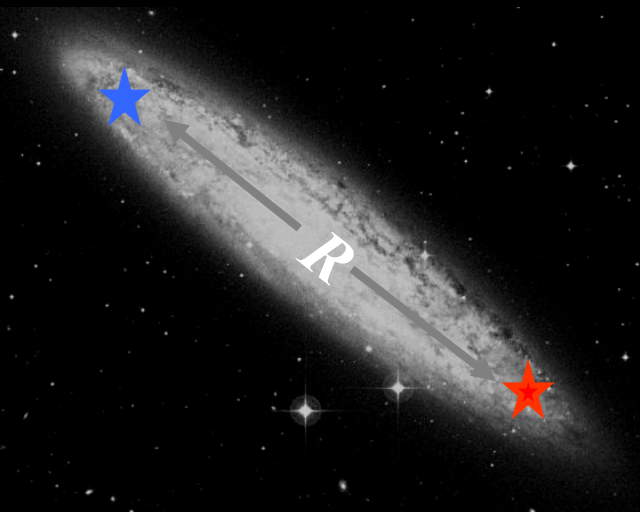
NGC253 in Sculptor






$$\frac{v^2}{R} = \frac{GM_{SUN}}{R^2}$$

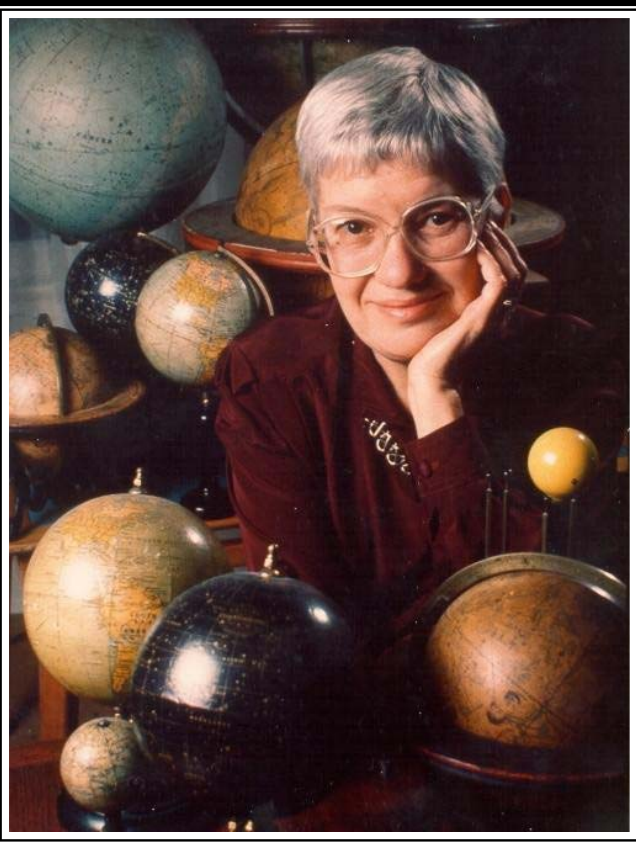
measure v & R  M_{SUN}



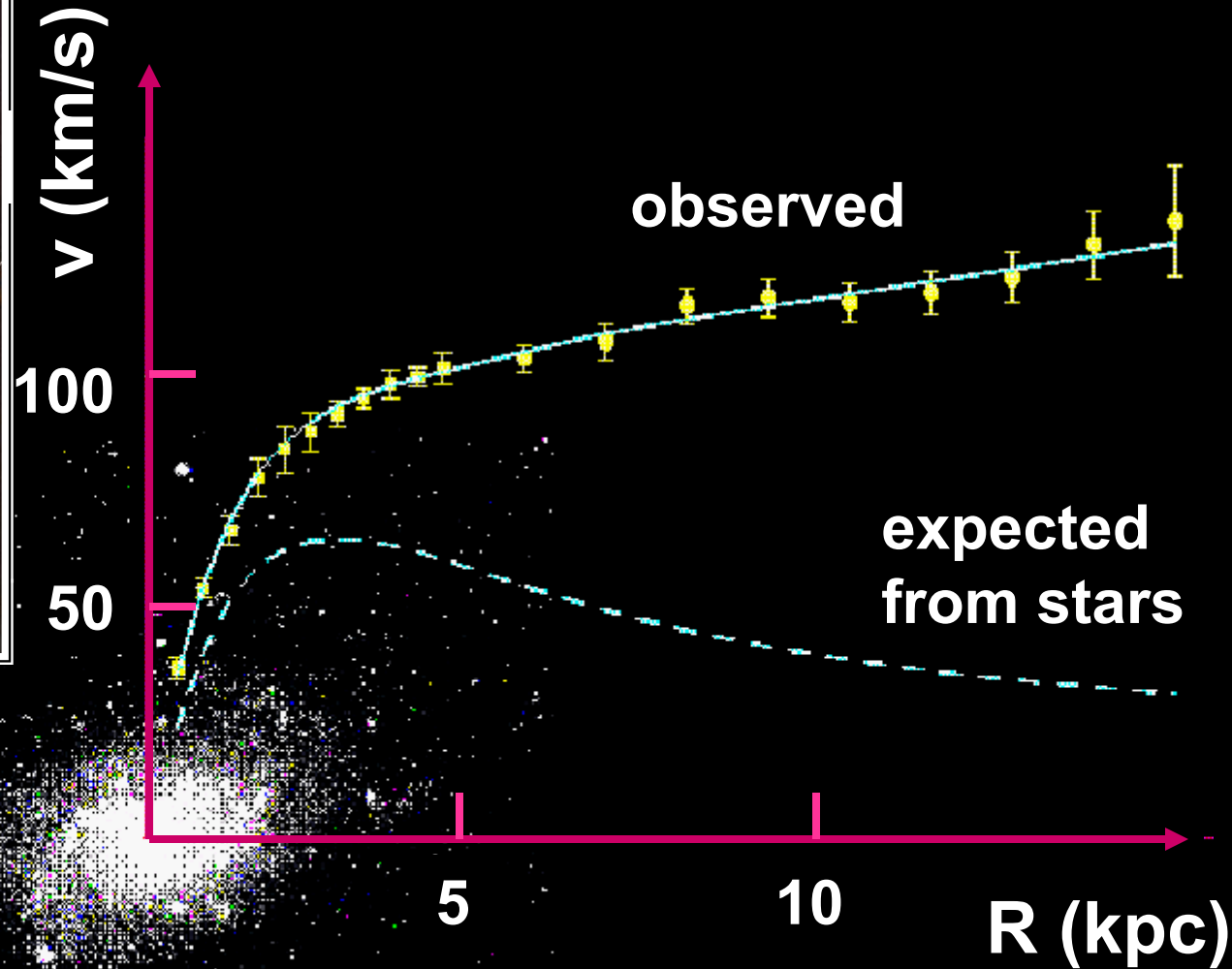
$$\frac{v^2}{R} = \frac{GM_{GALAXY}}{R^2}$$

measure v & R  M_{GALAXY}

The Invisible Universe

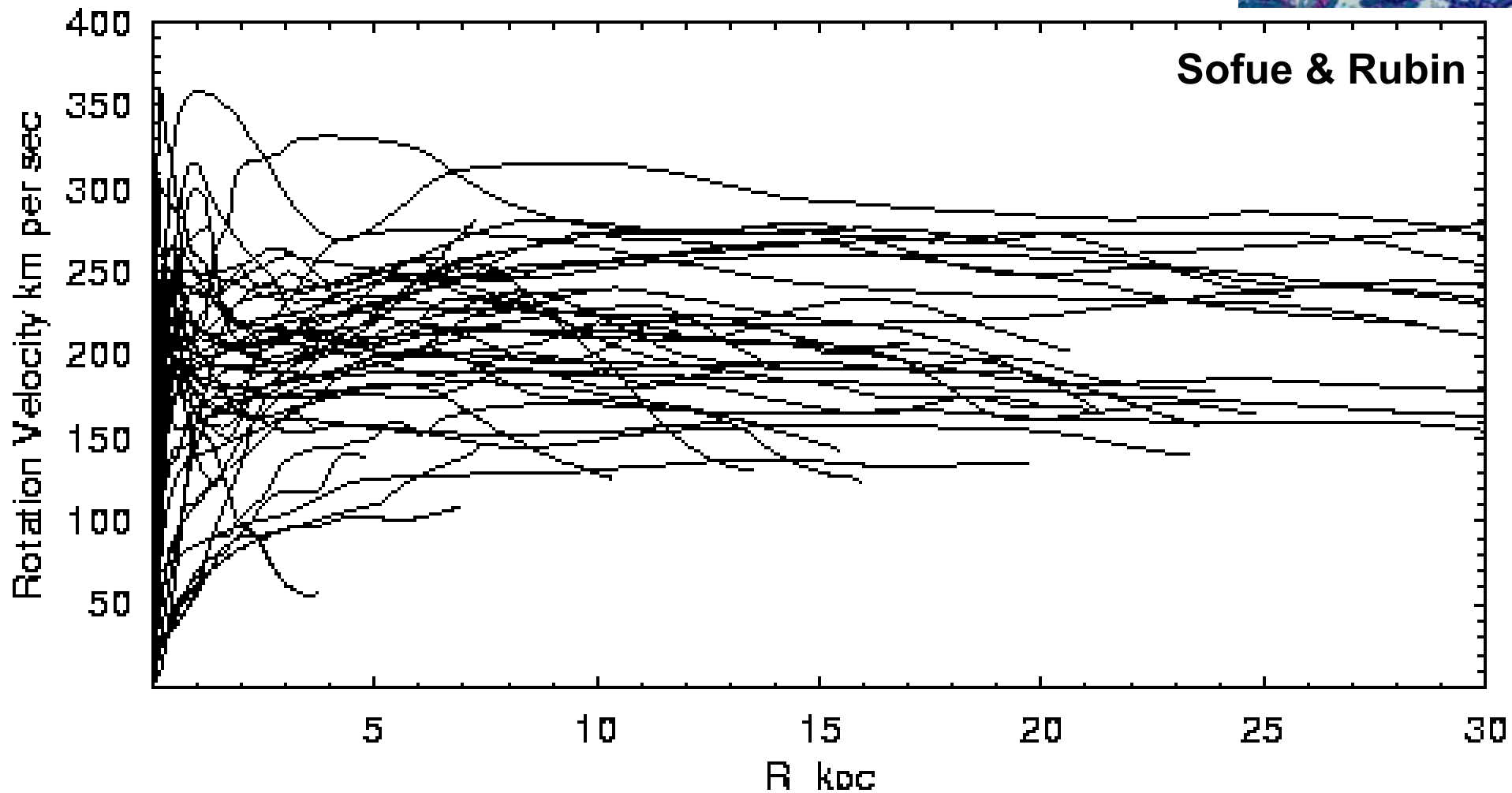


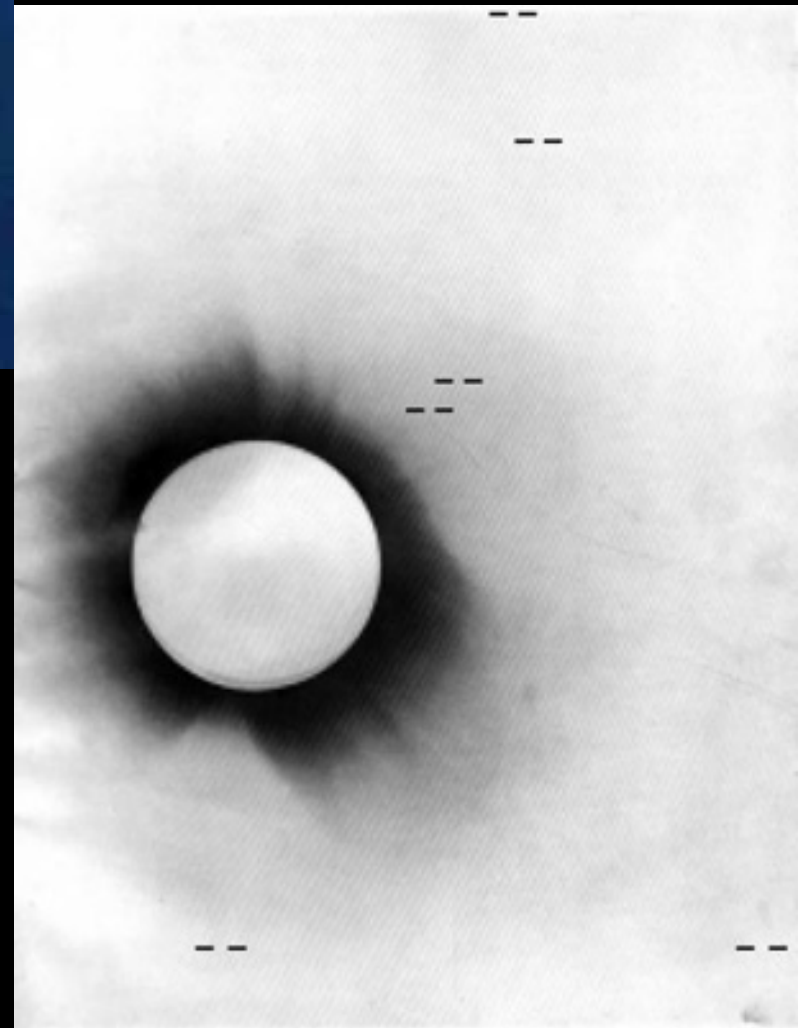
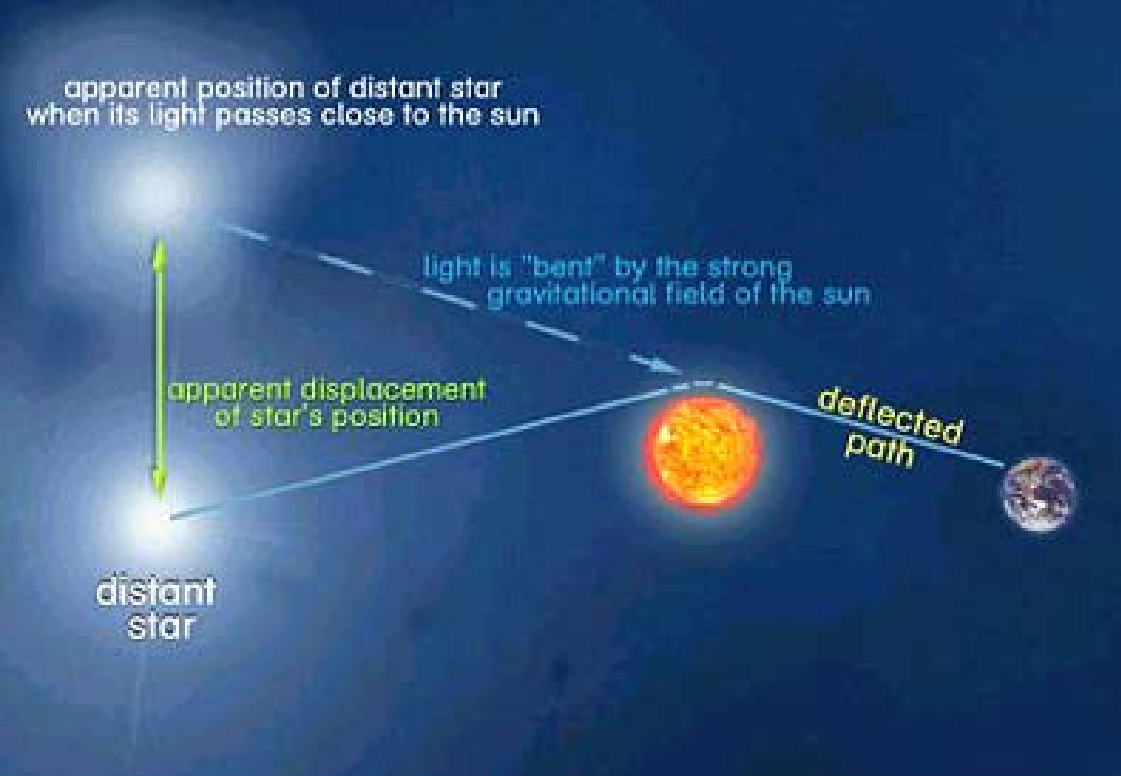
Vera Rubin



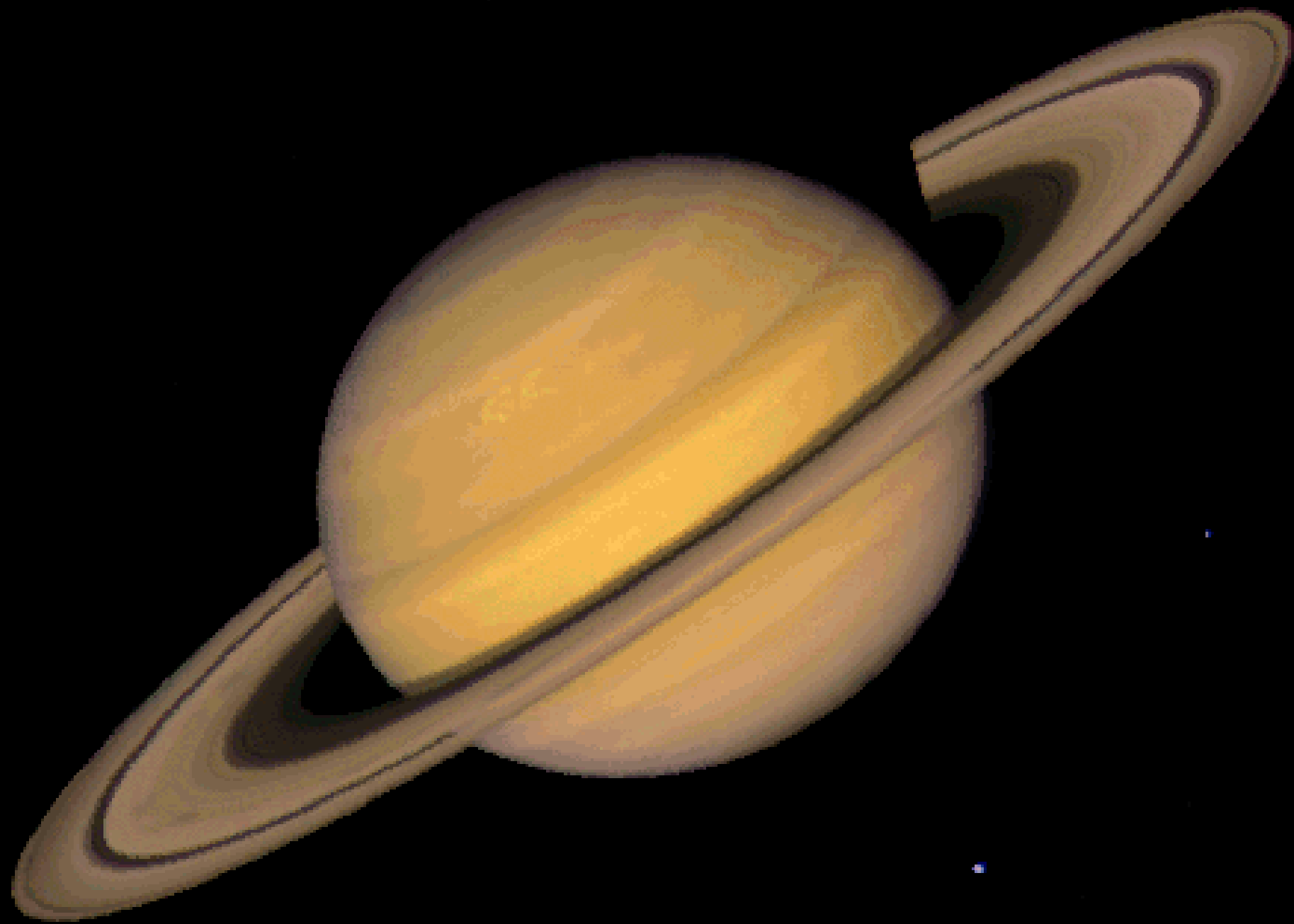
M33 rotation curve

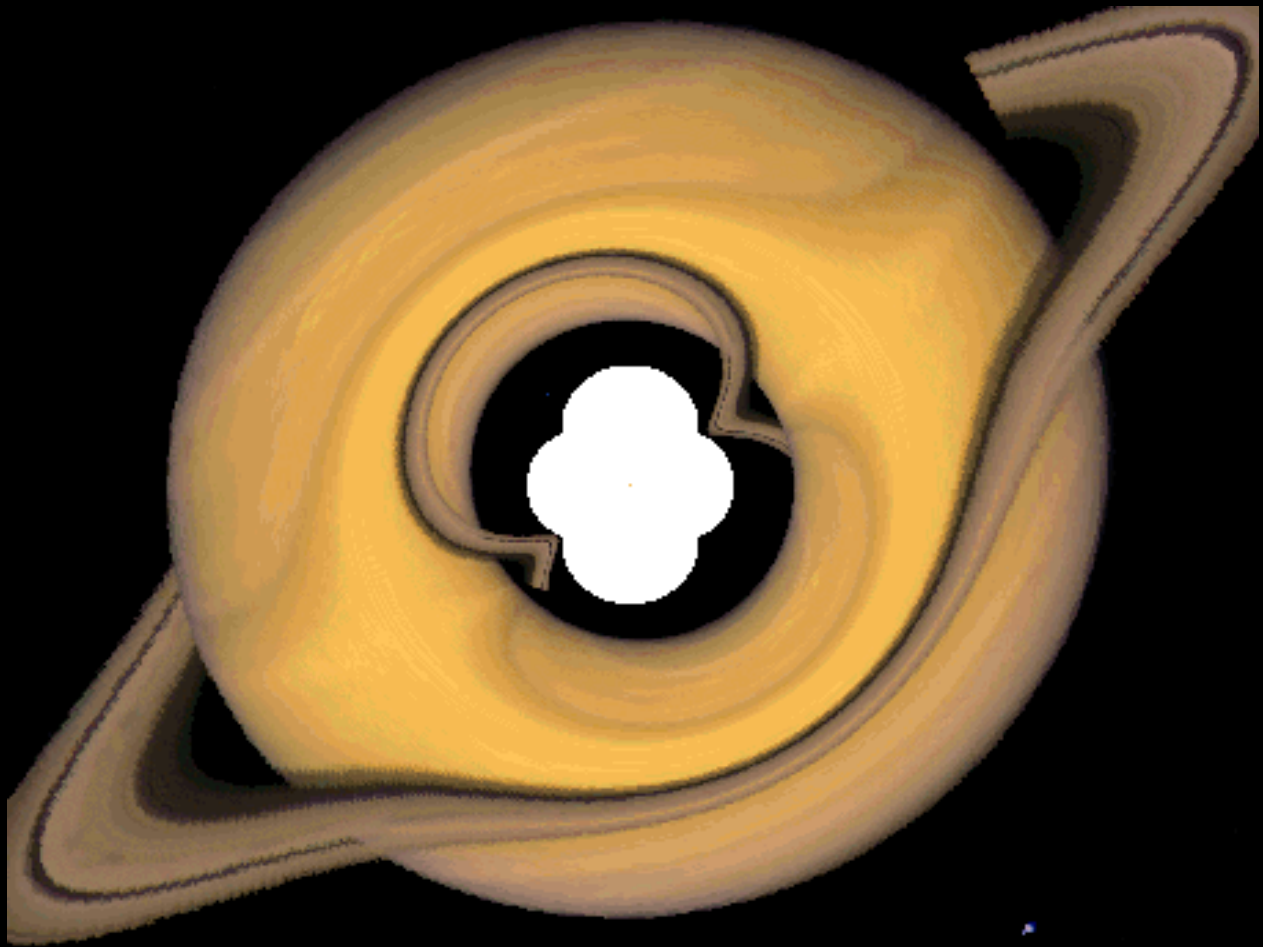
Rotation curves





1919 Eclipse Expedition





Gravitational Lensing





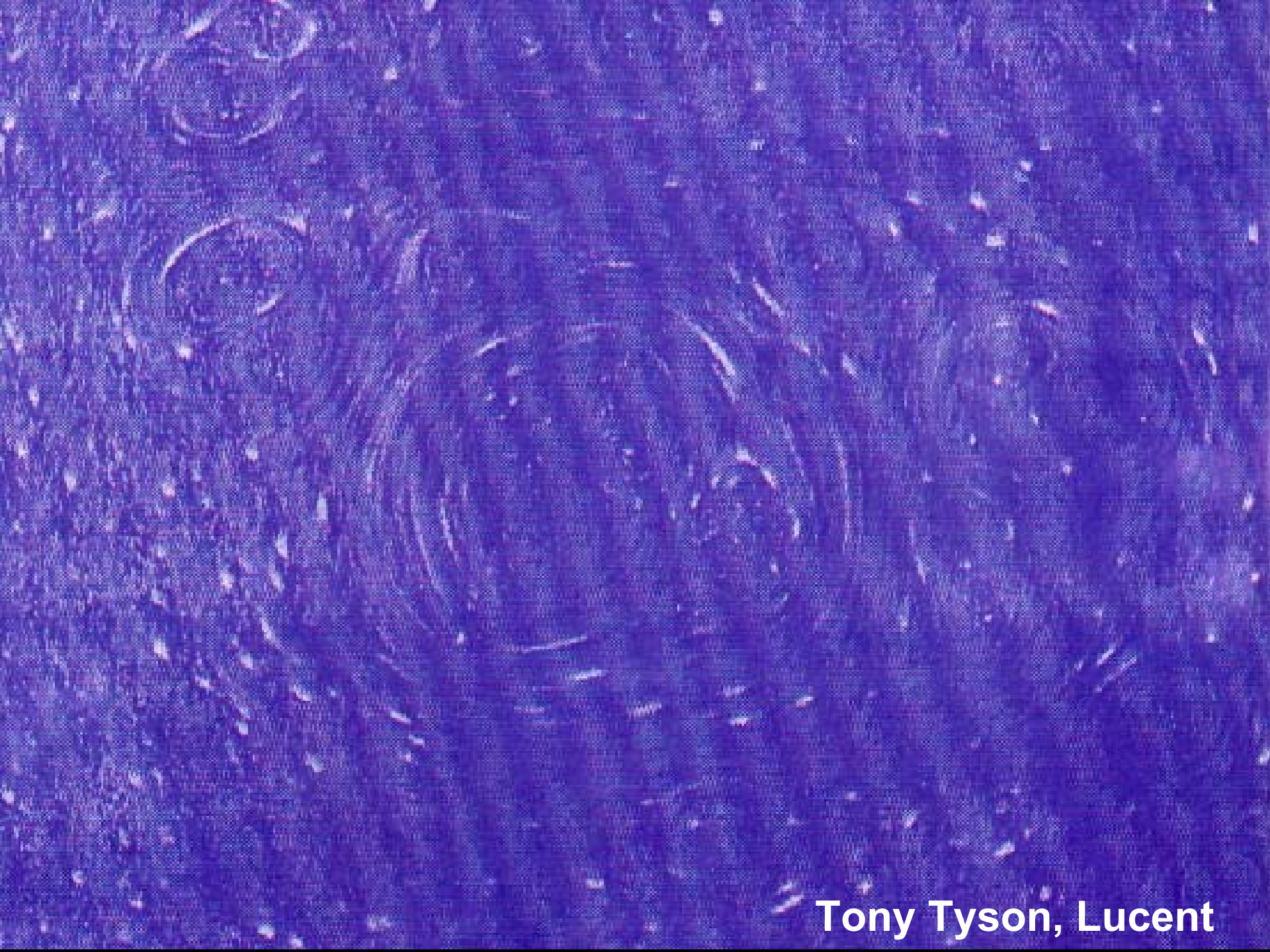
Gravitational Lens in Abell 2218

HST • WFPC2

PF95-14 • ST ScI OPO • April 5, 1995 • W. Couch (UNSW), NASA



Gravitational Lens
Galaxy Cluster 0024+1654
Hubble Space Telescope • WFPC2

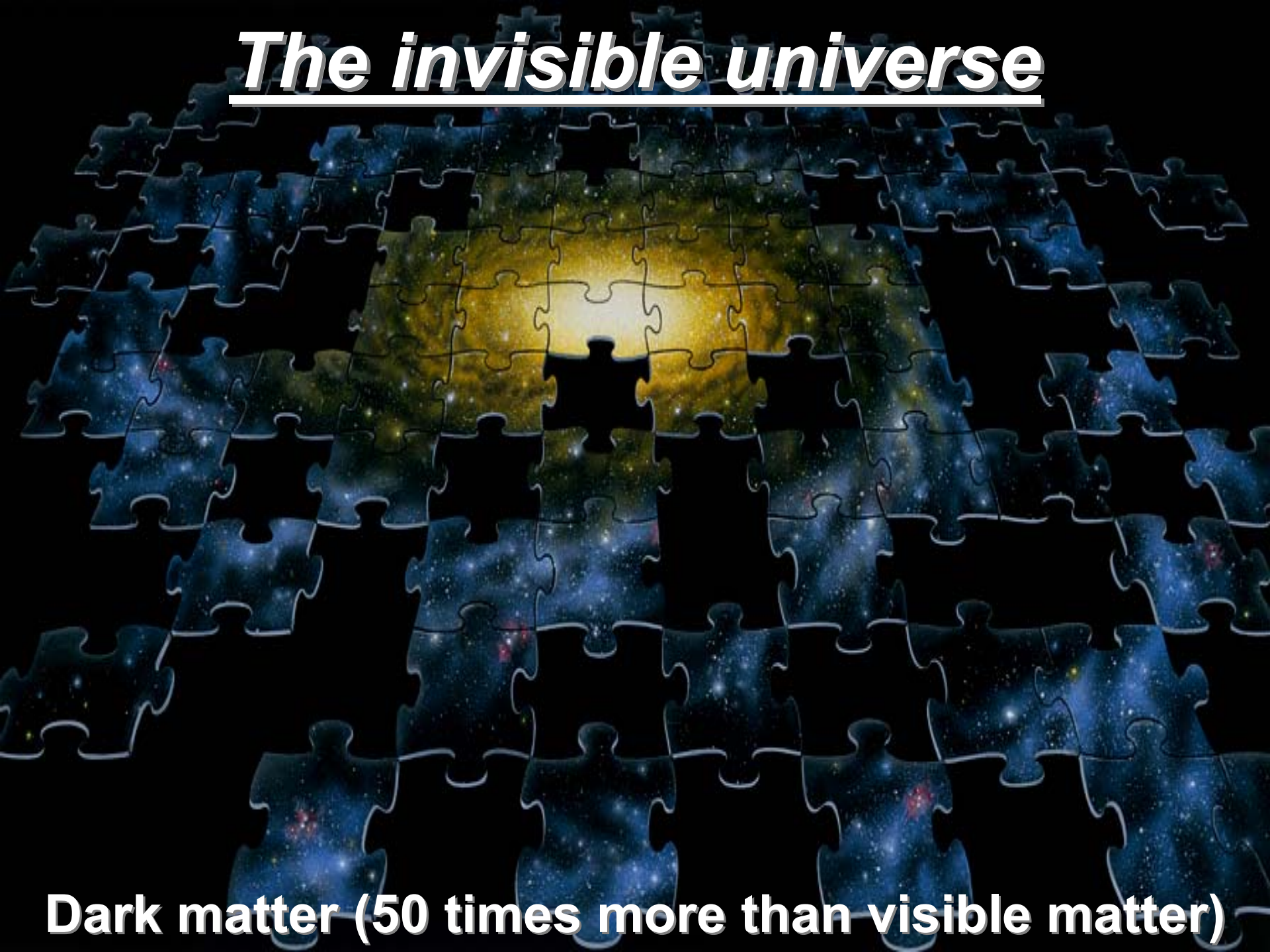


Tony Tyson, Lucent



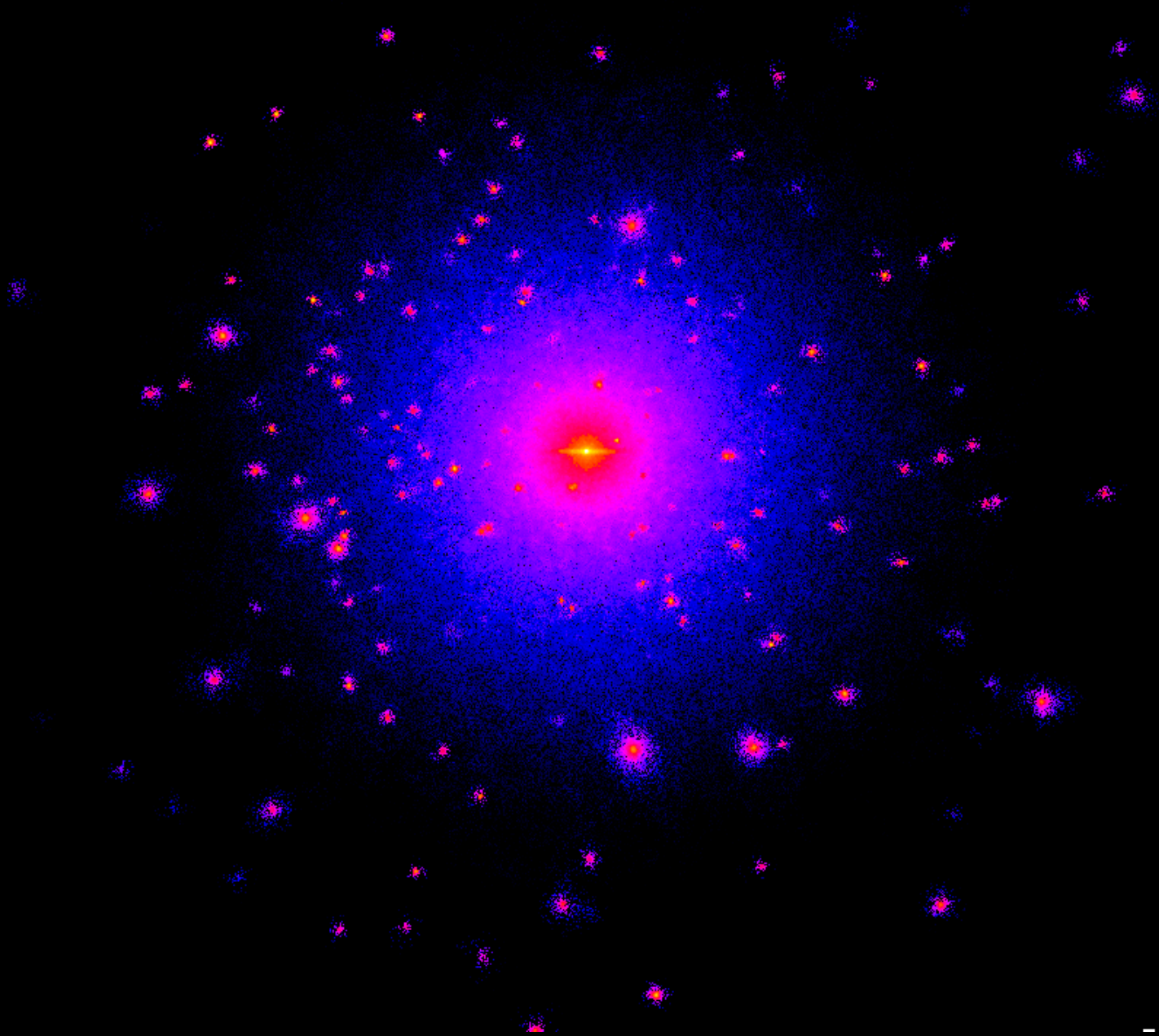
Most of the universe is dark!

The invisible universe



Dark matter (50 times more than visible matter)

If we could “see” dark matter

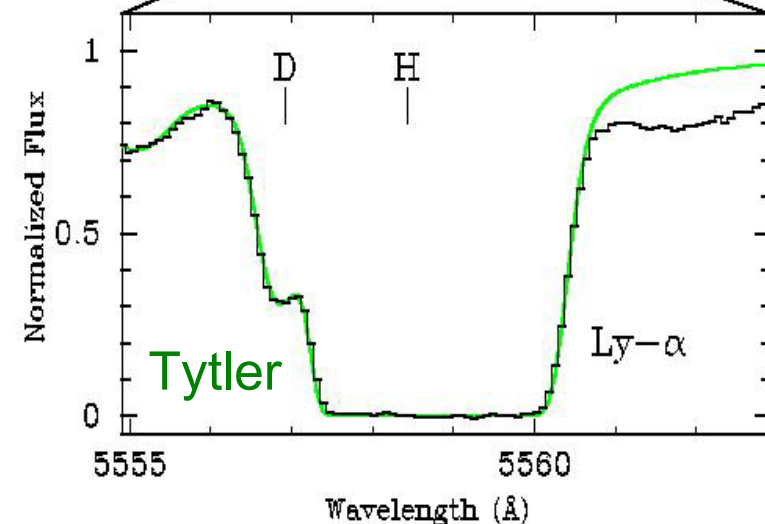
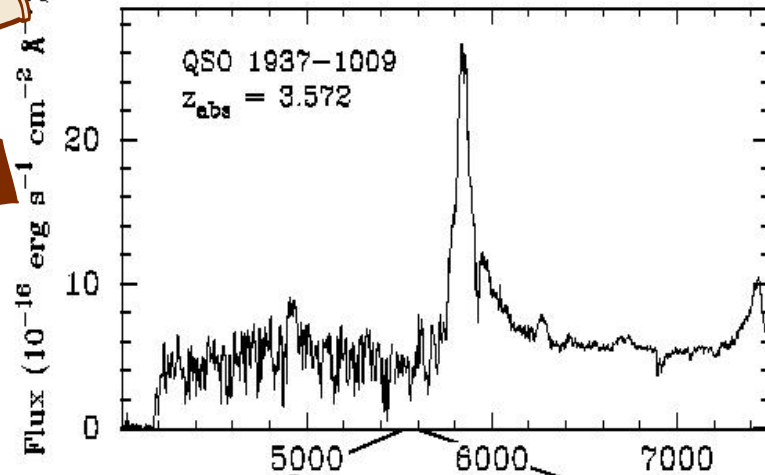
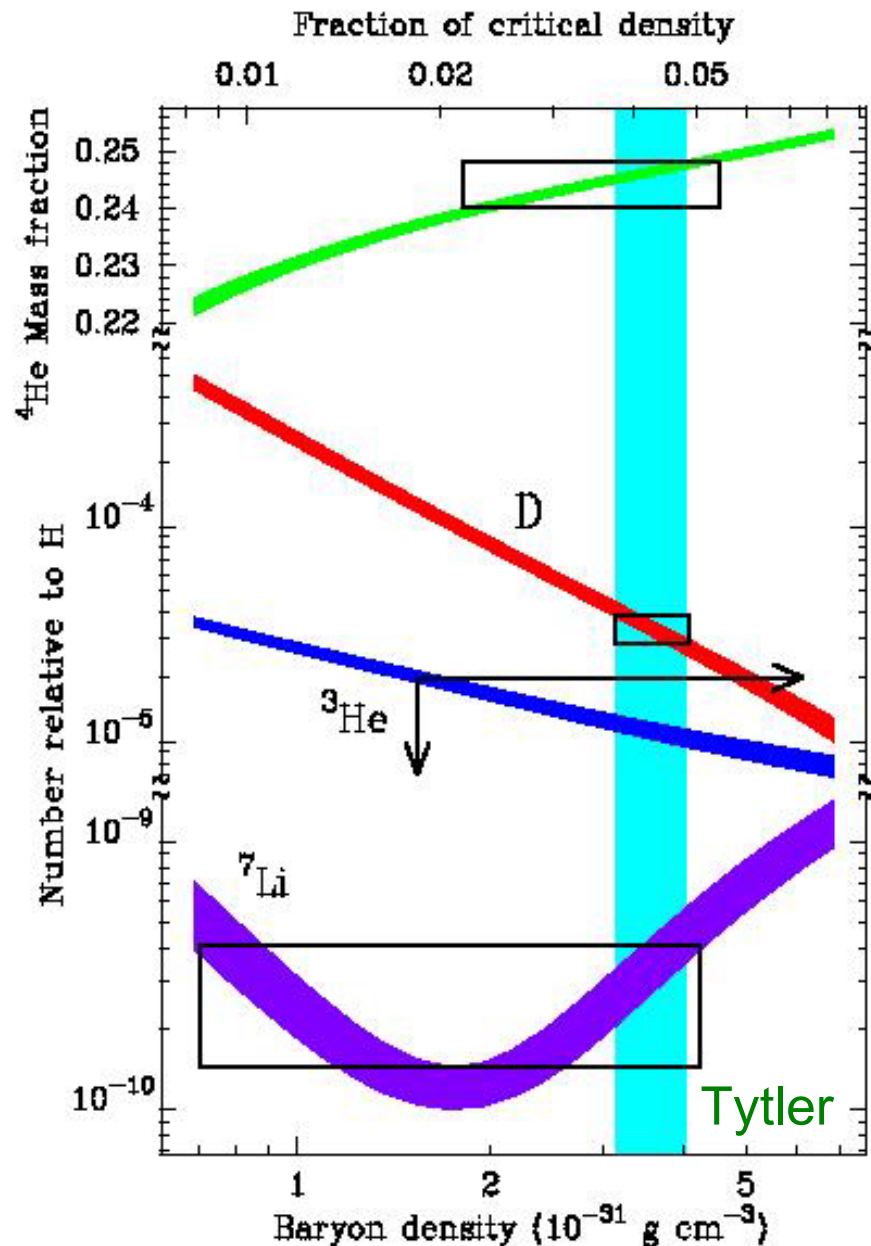


Most of the universe is dark!

Most of the universe is dark!

It ain't even normal stuff!

Big Bang Nucleosynthesis



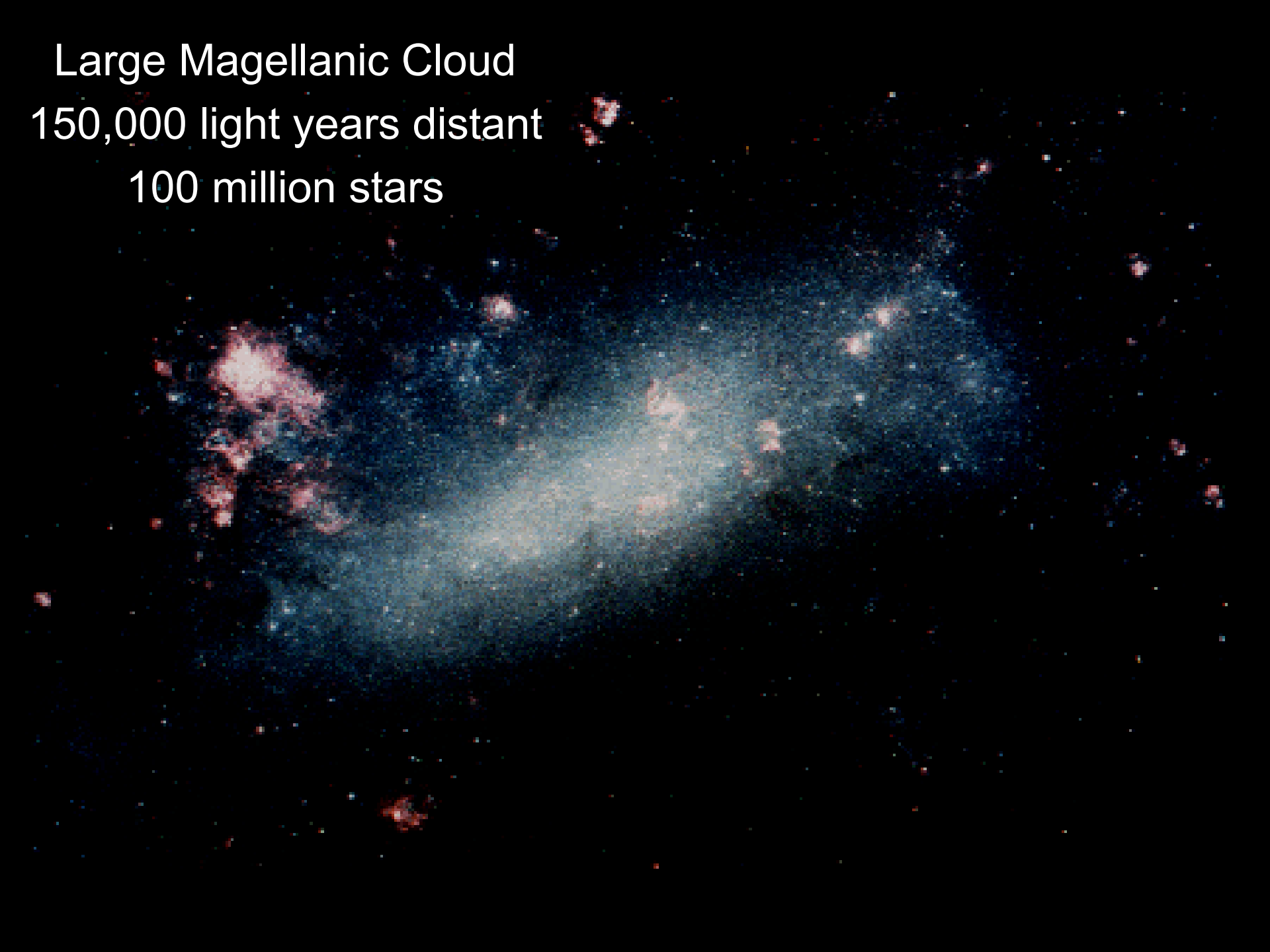
Dark matter?

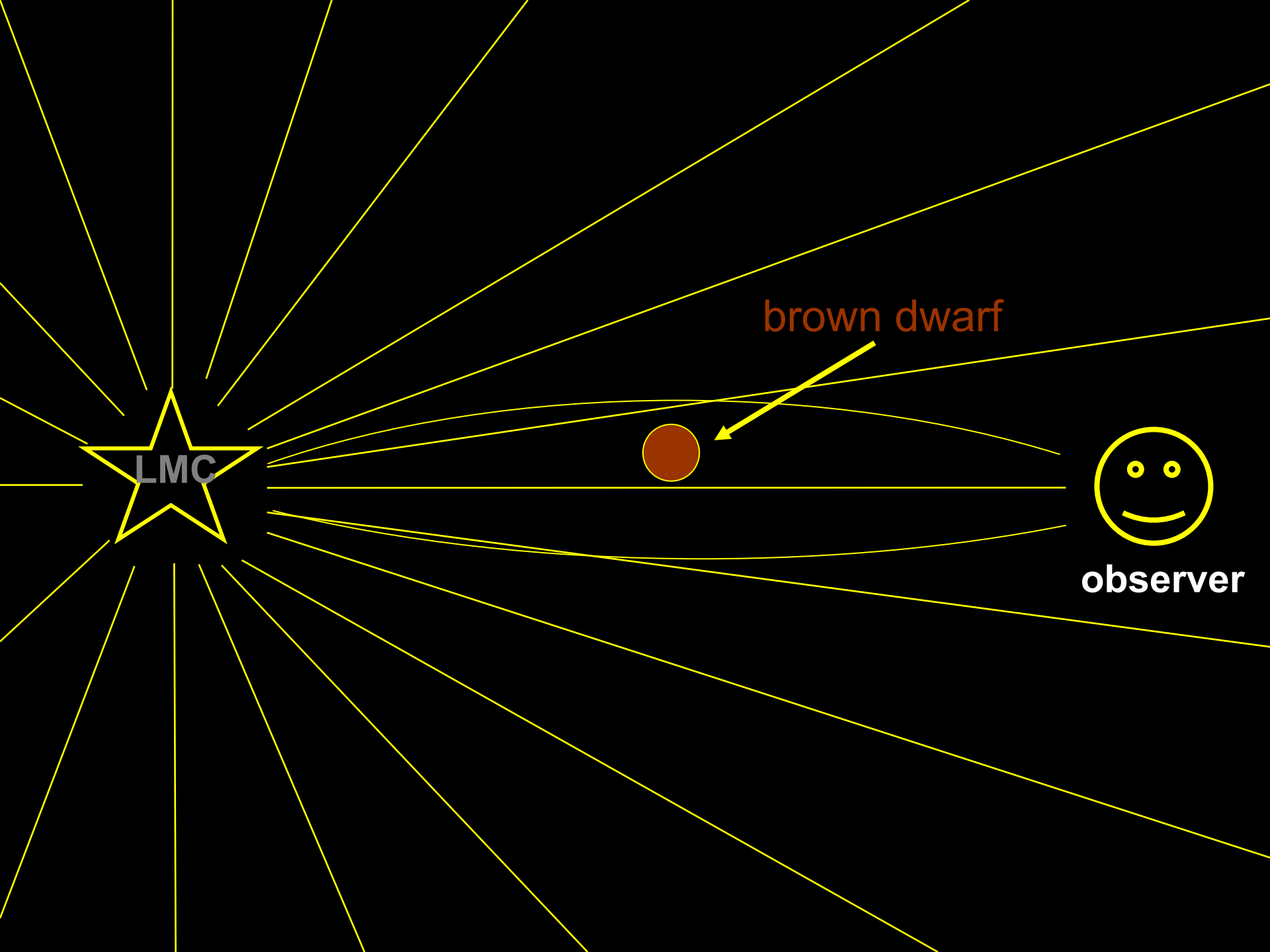
- Modified Newtonian dynamics
 - Planets
 - Dwarf stars
 - ~~White~~ brown red white stars
 - Black holes
- gravitational microlensing

Large Magellanic Cloud

150,000 light years distant

100 million stars





LMC

brown dwarf

observer

Day 387.6

Day 392.4

Day 420.4

Day 425.5

Day 428.4

Day 430.5

Day 432.7

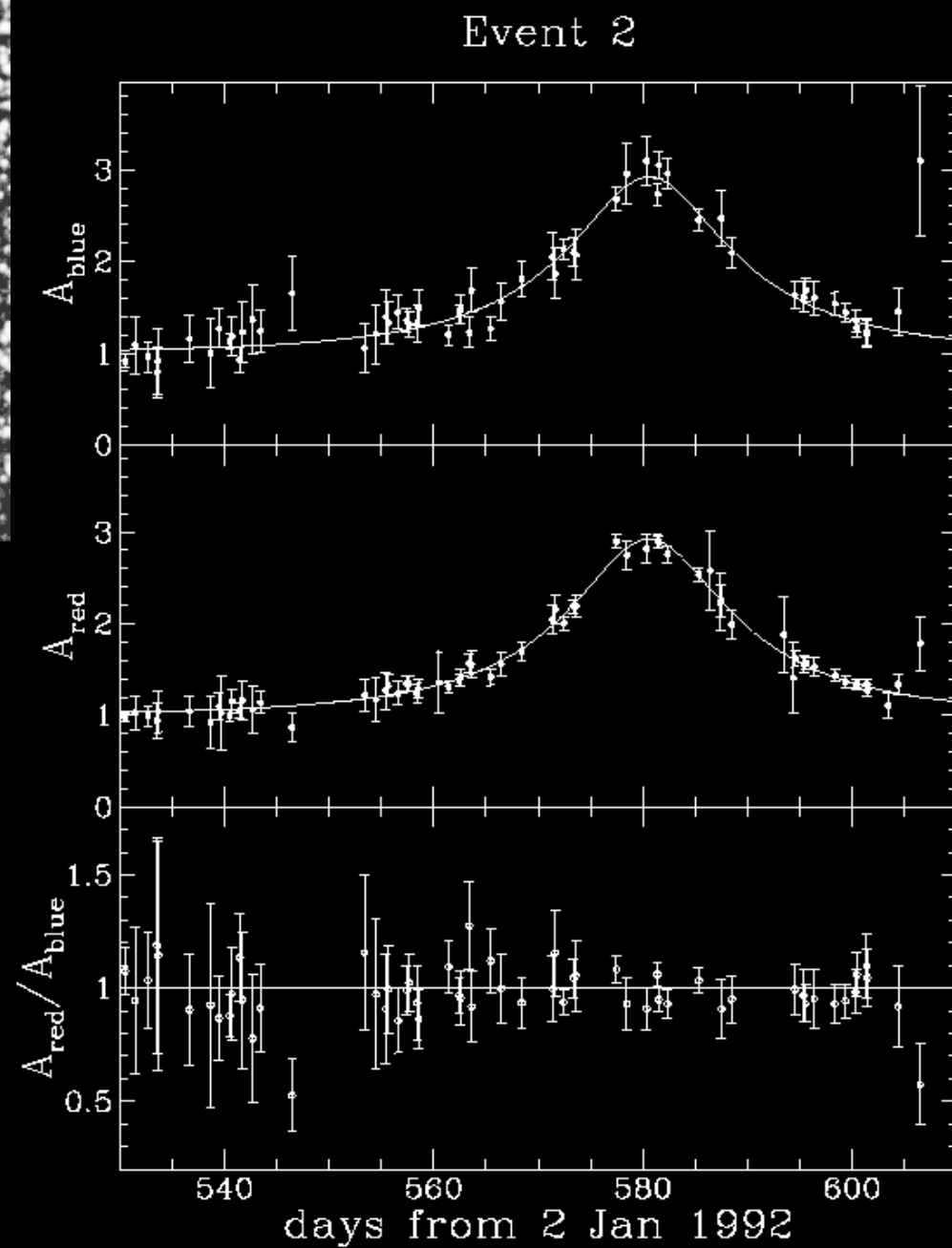
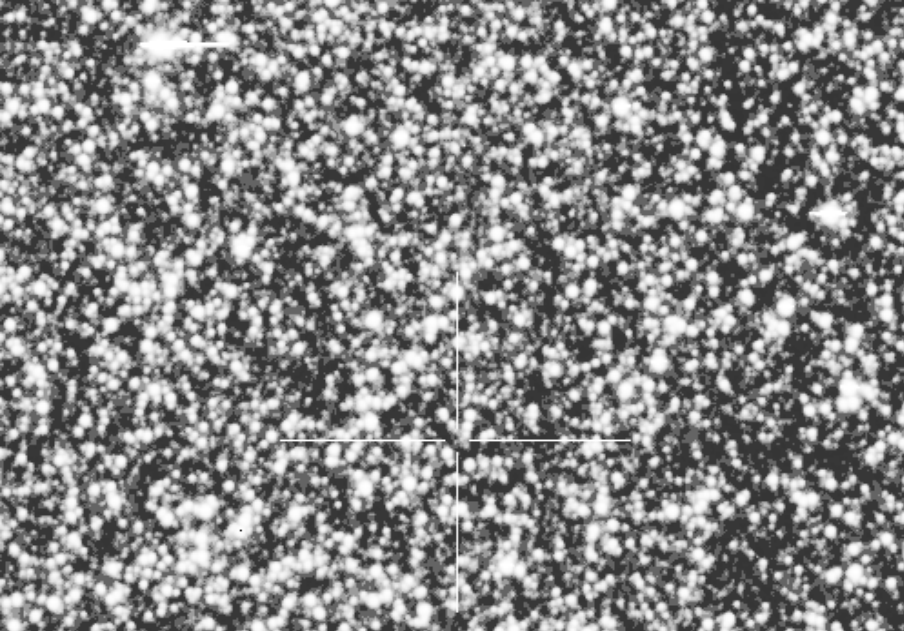
Day 435.4

Day 438.4

Day 442.6

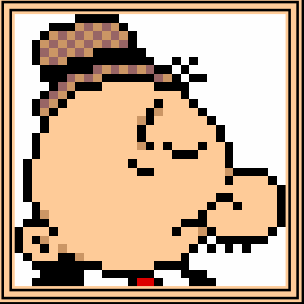
Day 457.5

Day 477.4

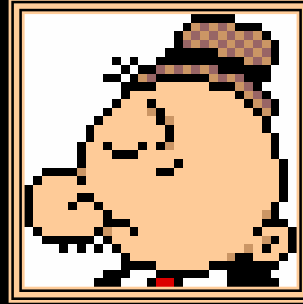


Most of the universe is dark !

- Modified Newtonian dynamics
- Planets
- Size challenged stars
 - brown red white
- Black holes
- Fossil remnant of the big bang



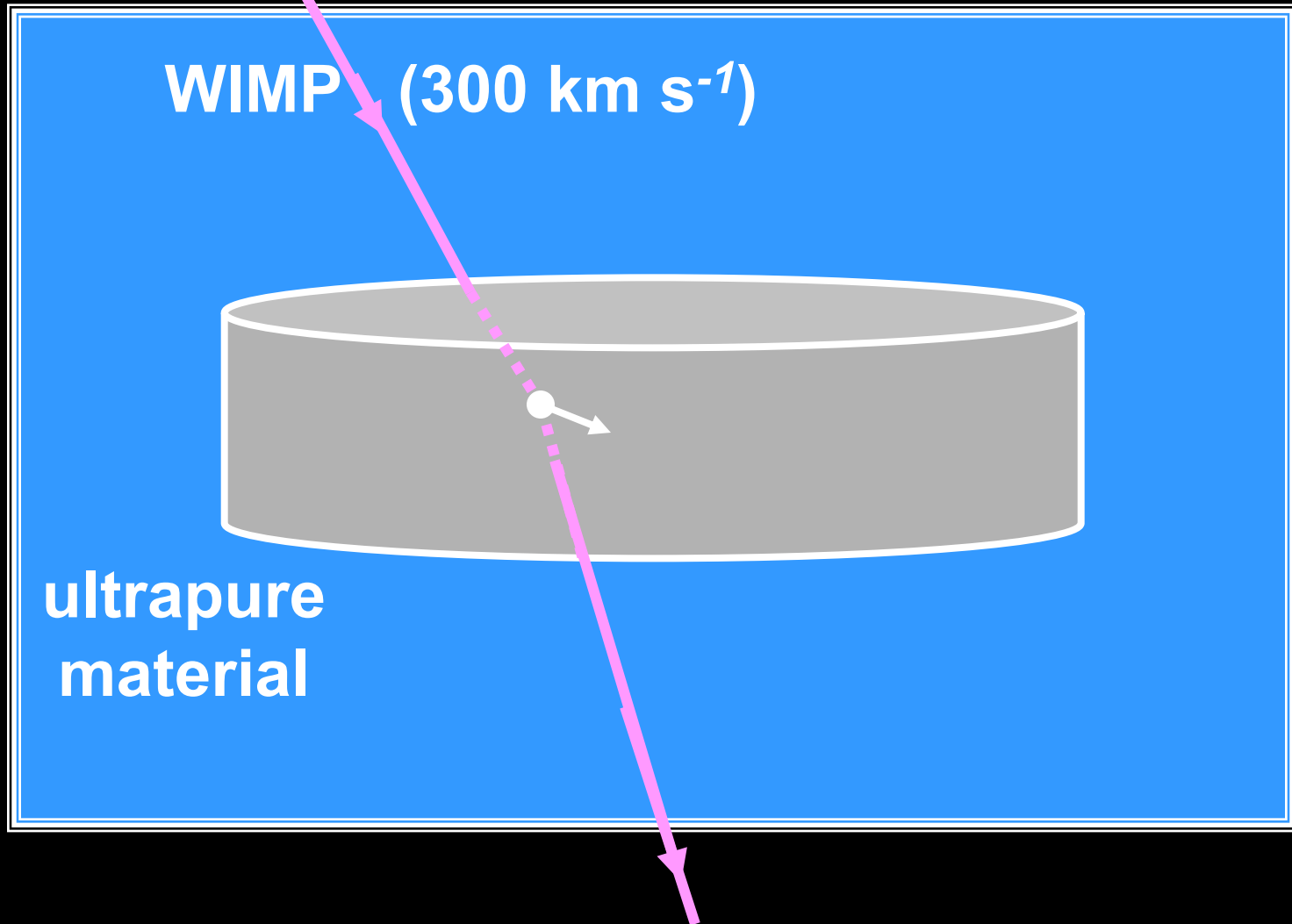
A WIMPY IDEA



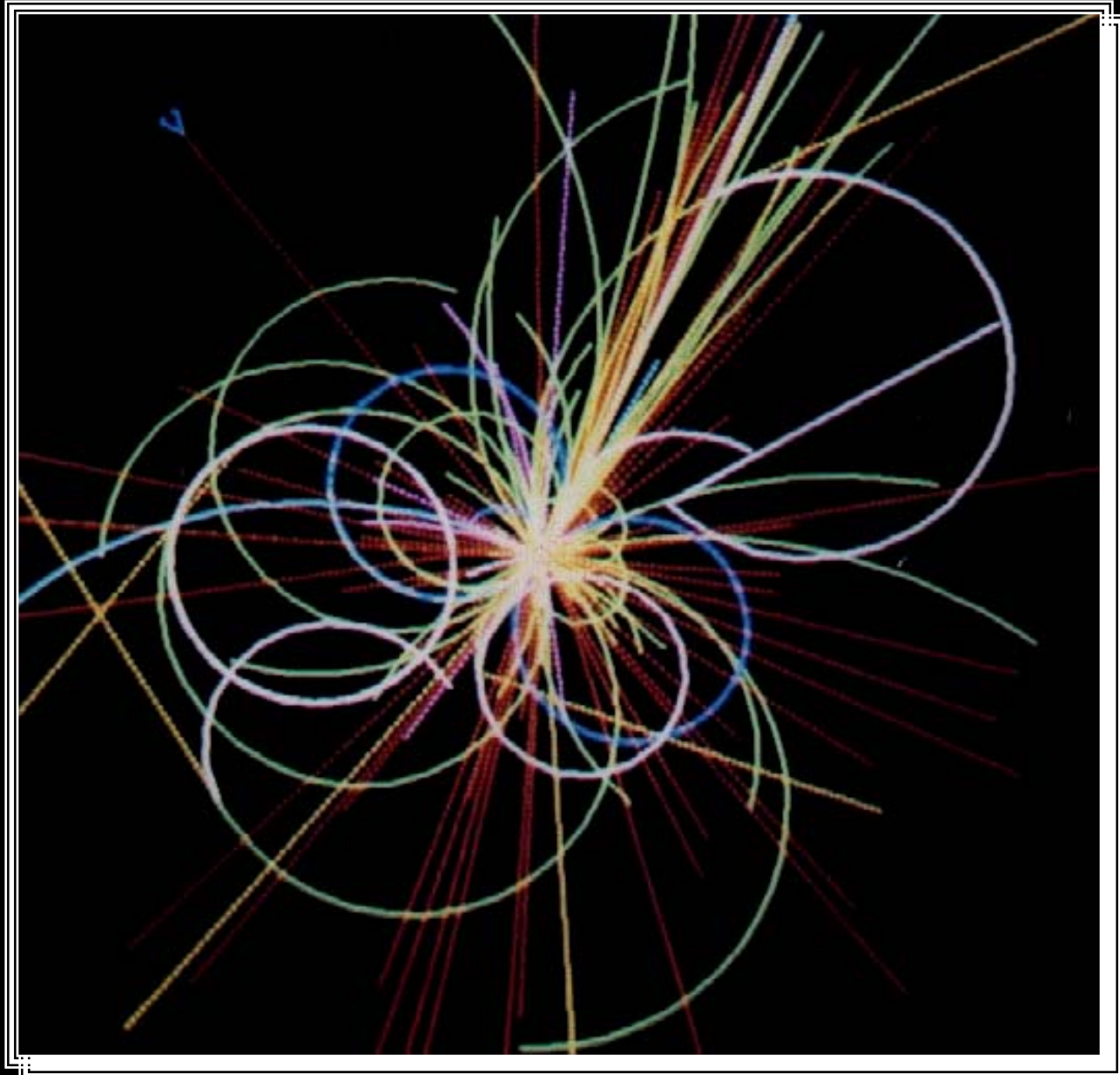
- Most of the universe is *invisible*
- Dominated by the rest mass of an elementary particle
 - present in the primordial soup
 - massive
 - neutral
 - weakly interacting
 - slow
 - stable

W
I
M
P

Direct detection



Make wimps in the laboratory



Primordial soup

KNOWN INGREDIENTS:

56% QUARKS

16% GLUONS (STRONG FORCE)

9% ELECTRON-LIKE PARTICLES

9% W's AND Z's (WEAK FORCE)

5% NEUTRINOS

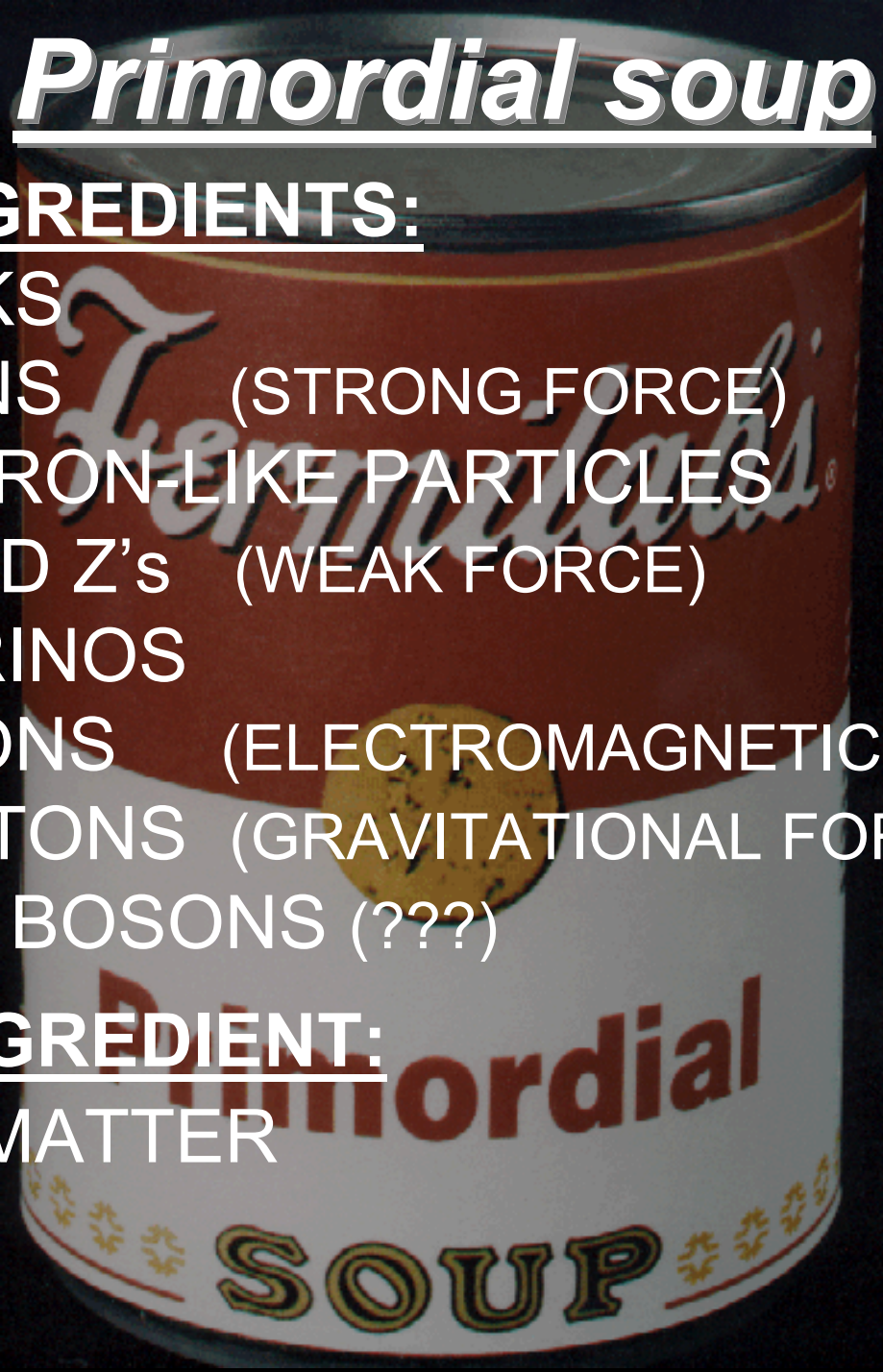
2% PHOTONS (ELECTROMAGNETIC FORCE)

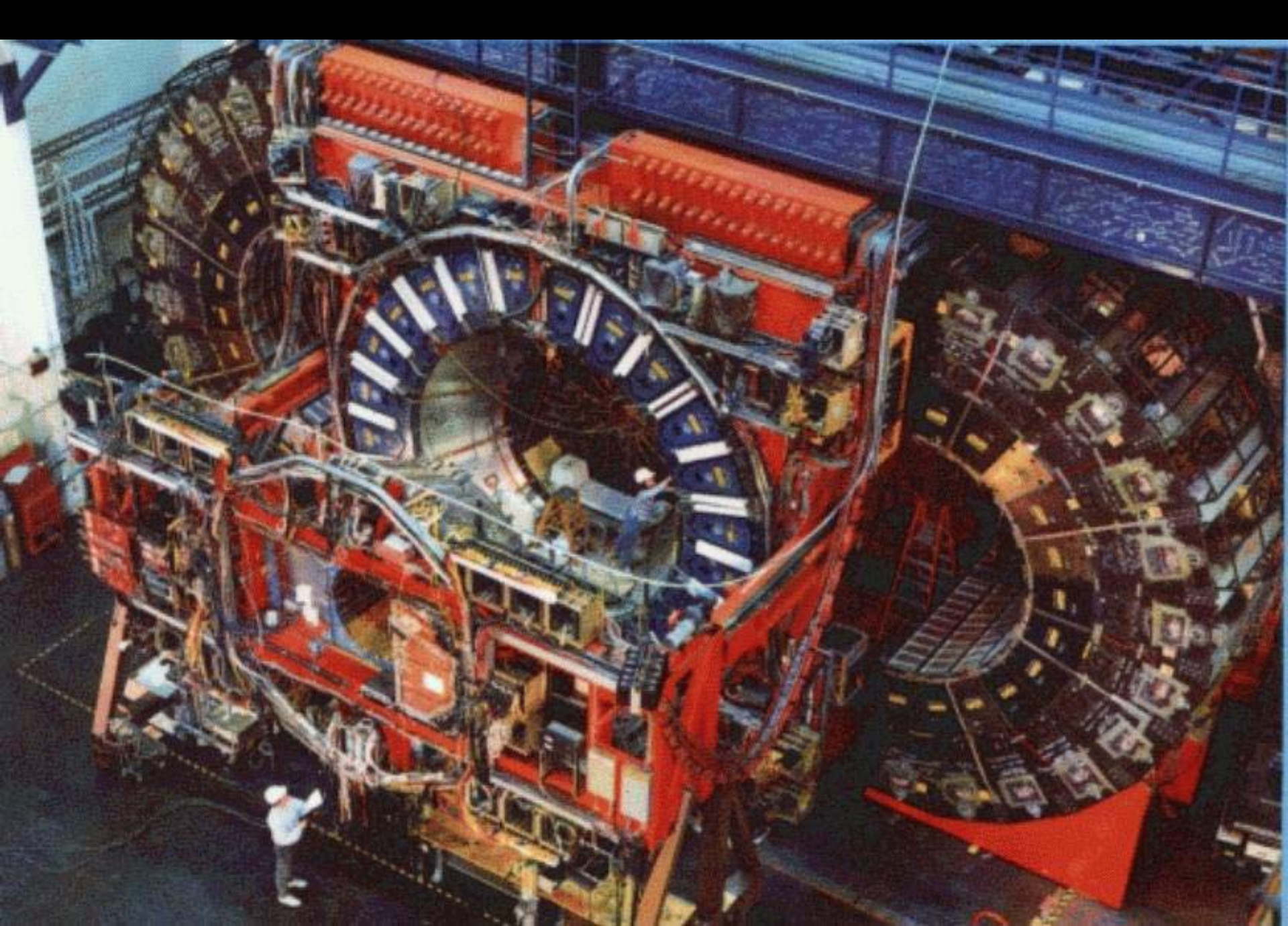
2% GRAVITONS (GRAVITATIONAL FORCE)

1% HIGGS BOSONS (???)

SECRET INGREDIENT:

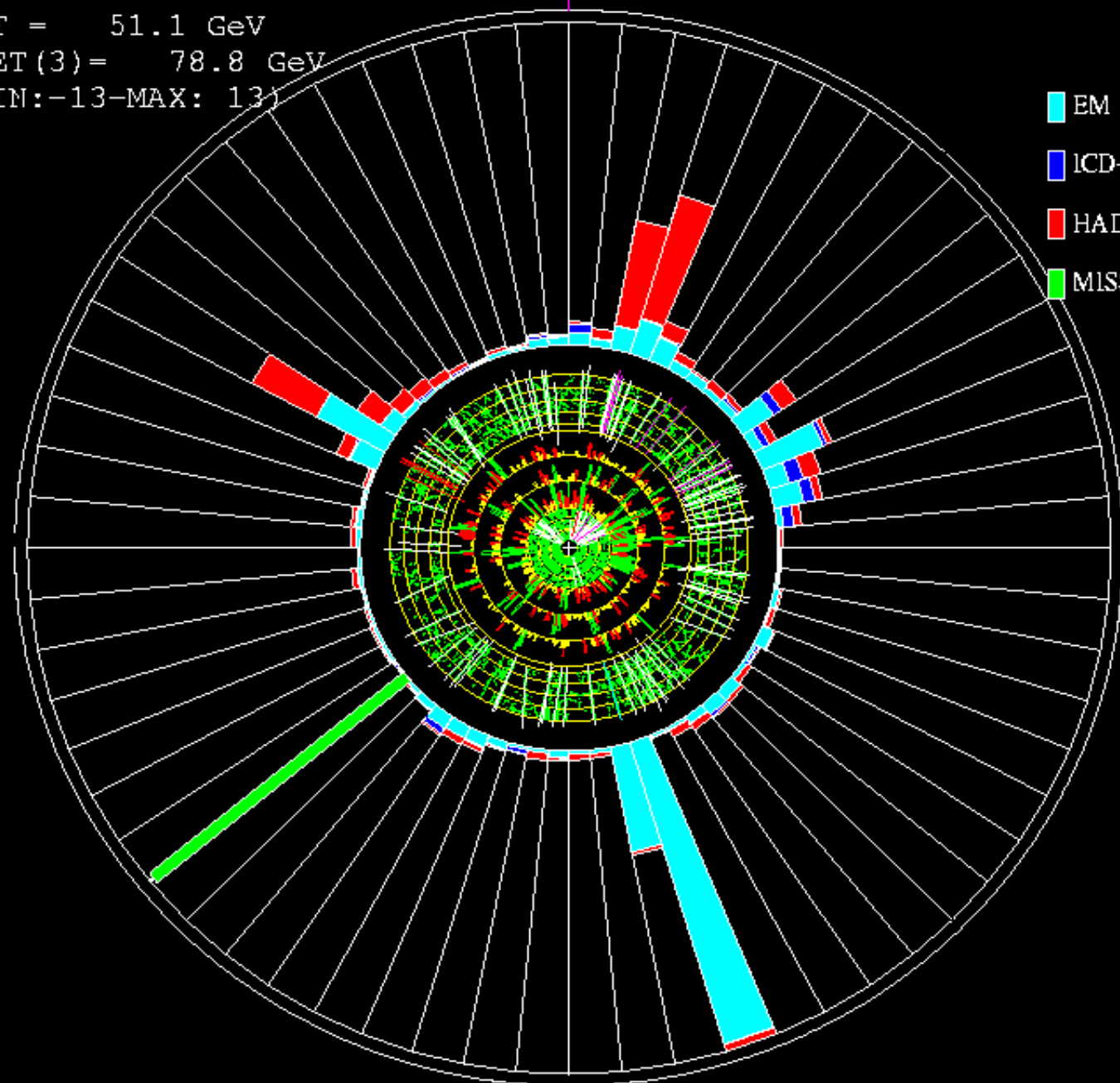
DARK MATTER



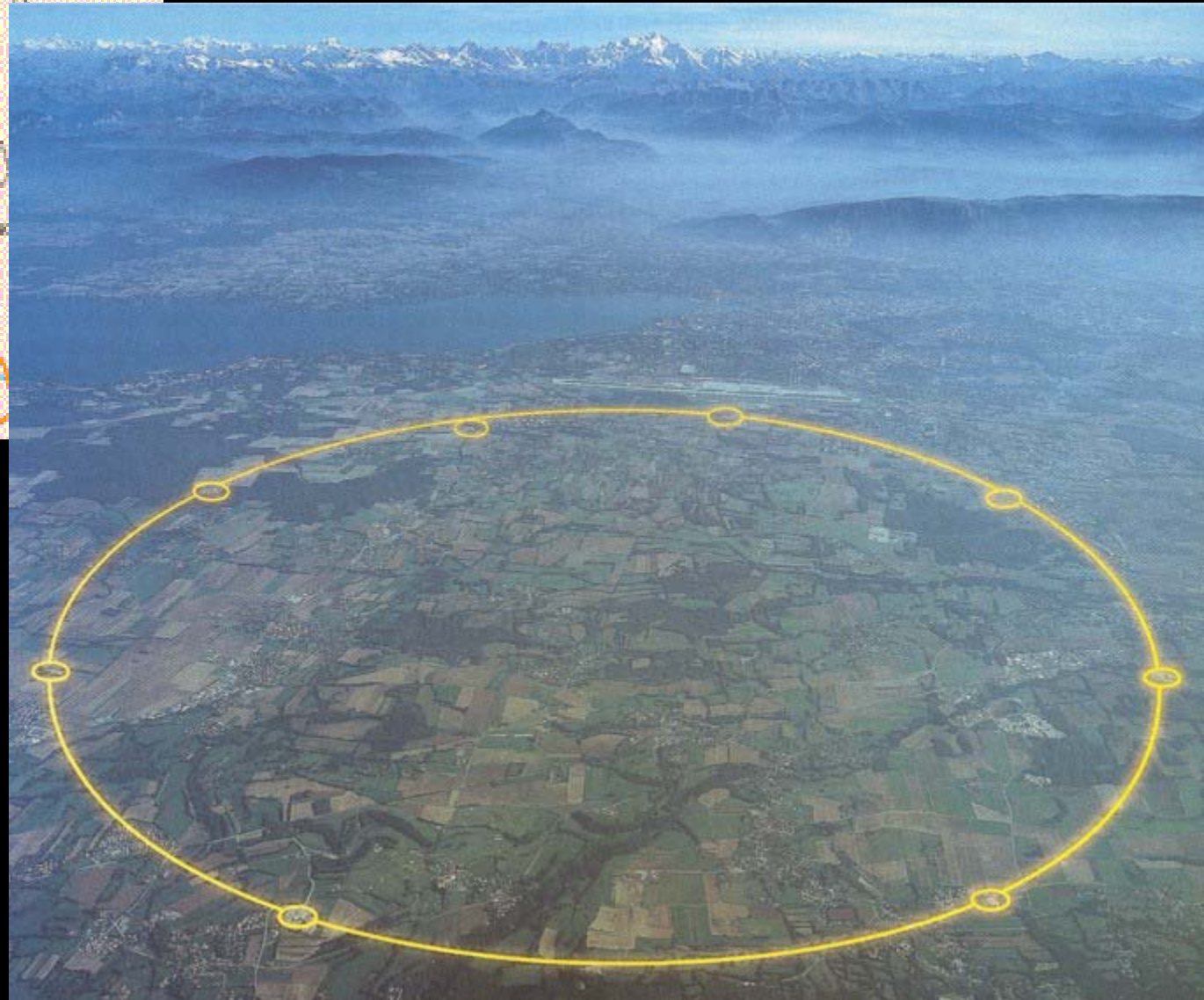
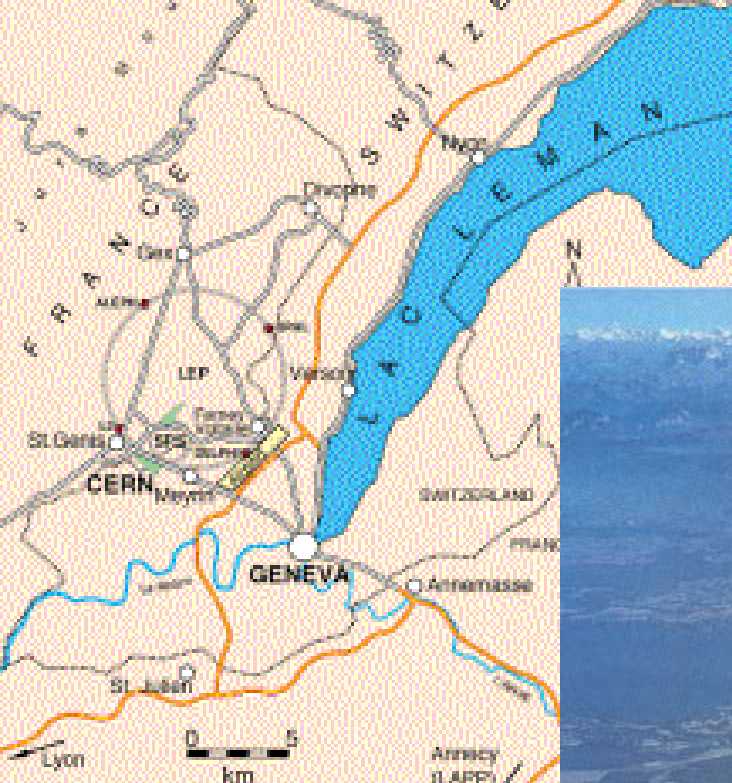


Max ET = 51.1 GeV
 MISS ET(3) = 78.8 GeV
 ETA (MIN:-13-MAX: 13)

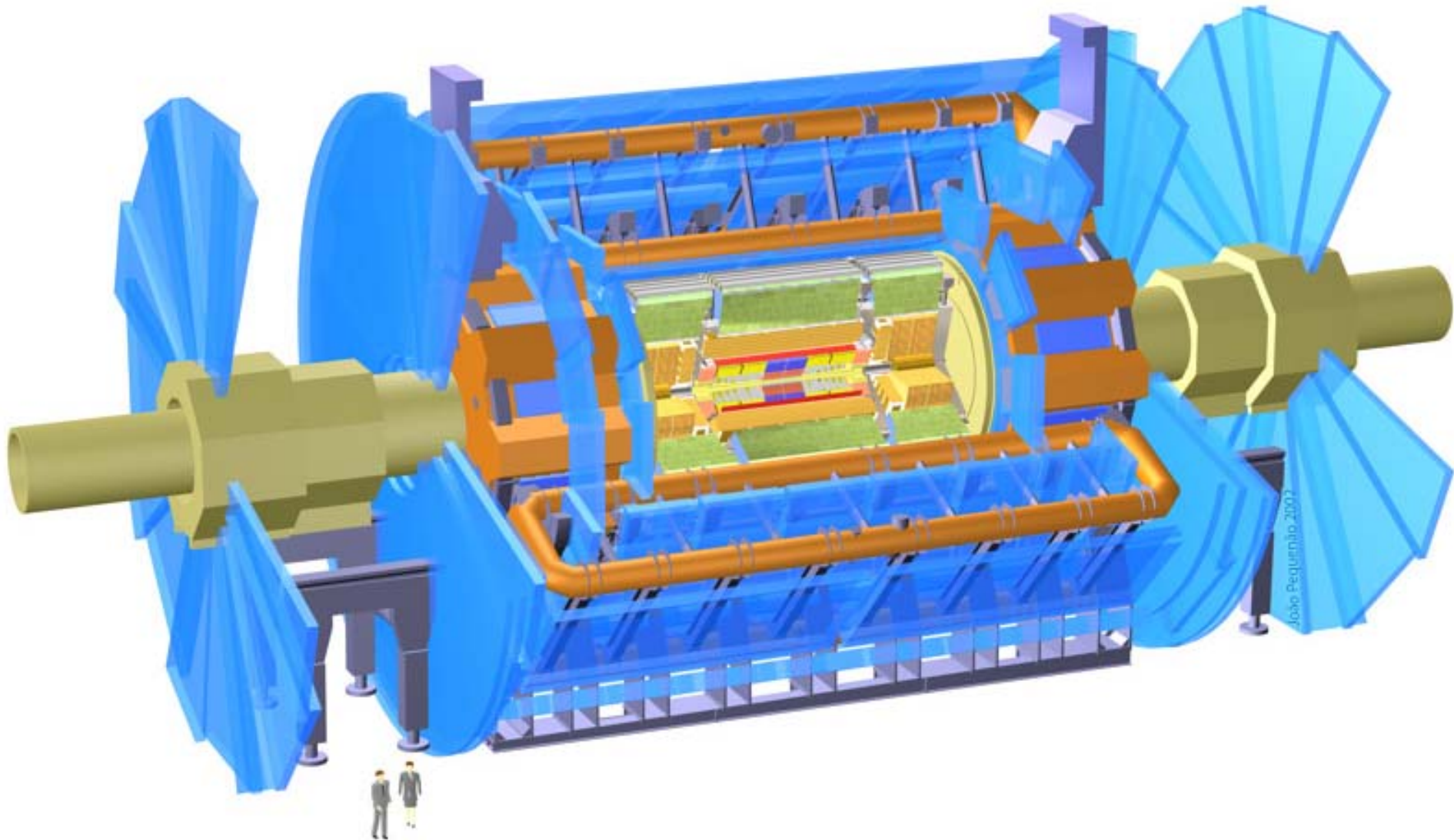
EM
 ICD+MG
 HAD
 MISS ET








LHC – 27 km circumference (size does matter)



Atlas Detector at CERN



Desperately seeking **SUSY**

photons		photinos
selectrons		electrons
squarks		quarks
gravitons		gravitinos
wino		W

Lightest superpartner *stable!*

Dark energy?

Space and time are related.

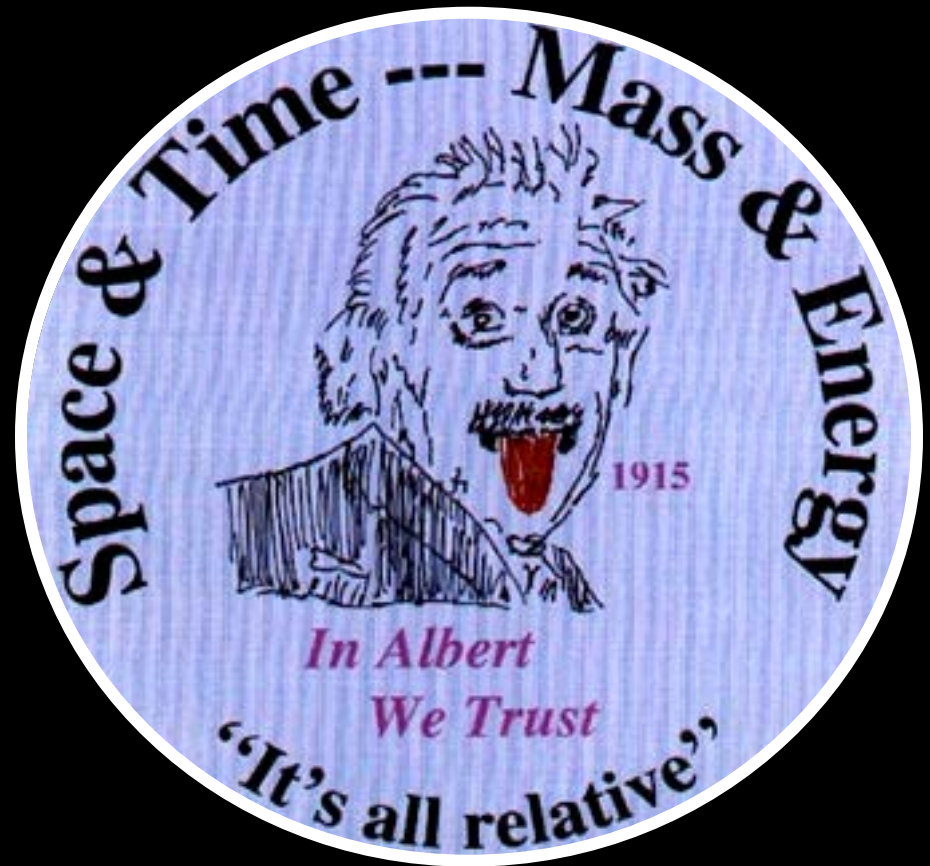
1905

Space is dynamical
(curved, warped, bent).

1915

Empty space has a weight.

1917



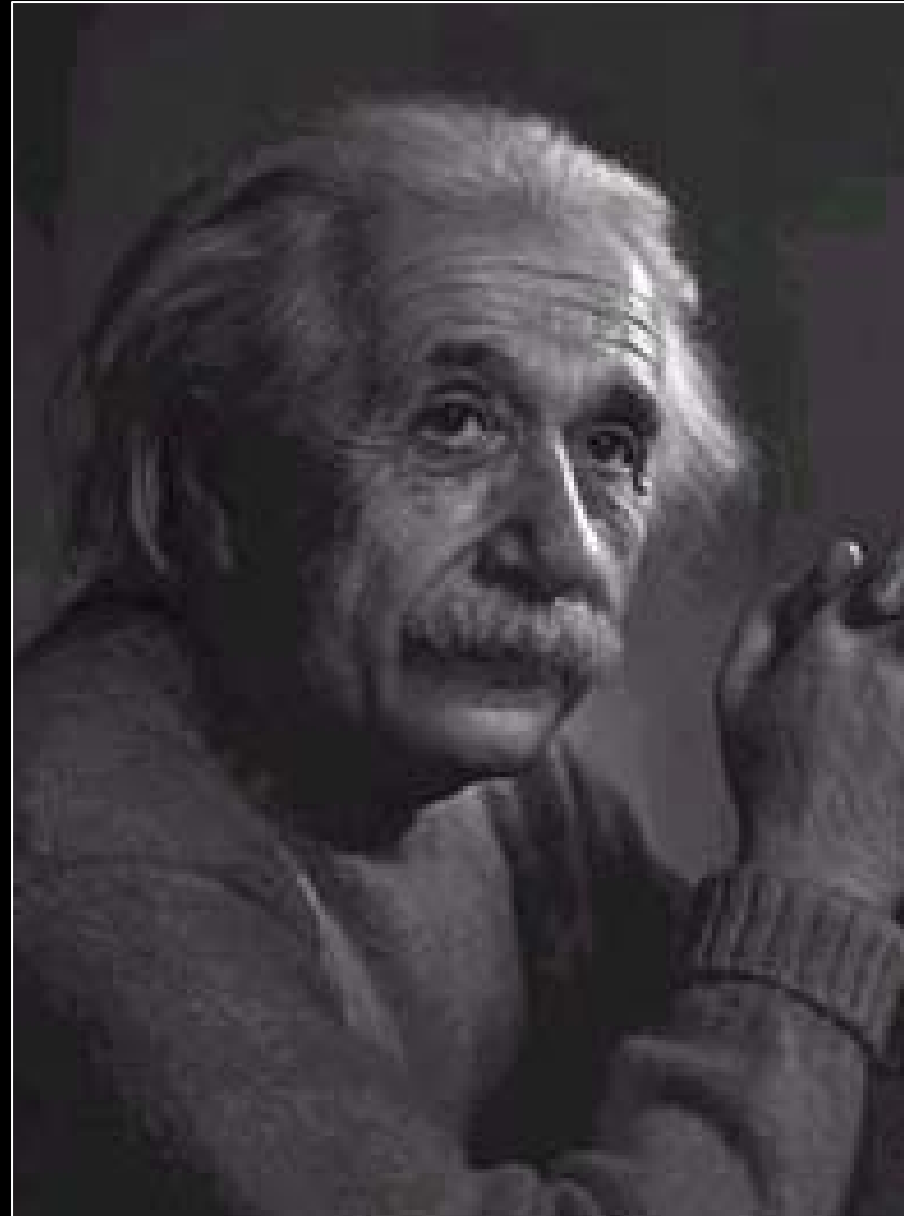
Dark energy

1917 Einstein proposed cosmological constant.

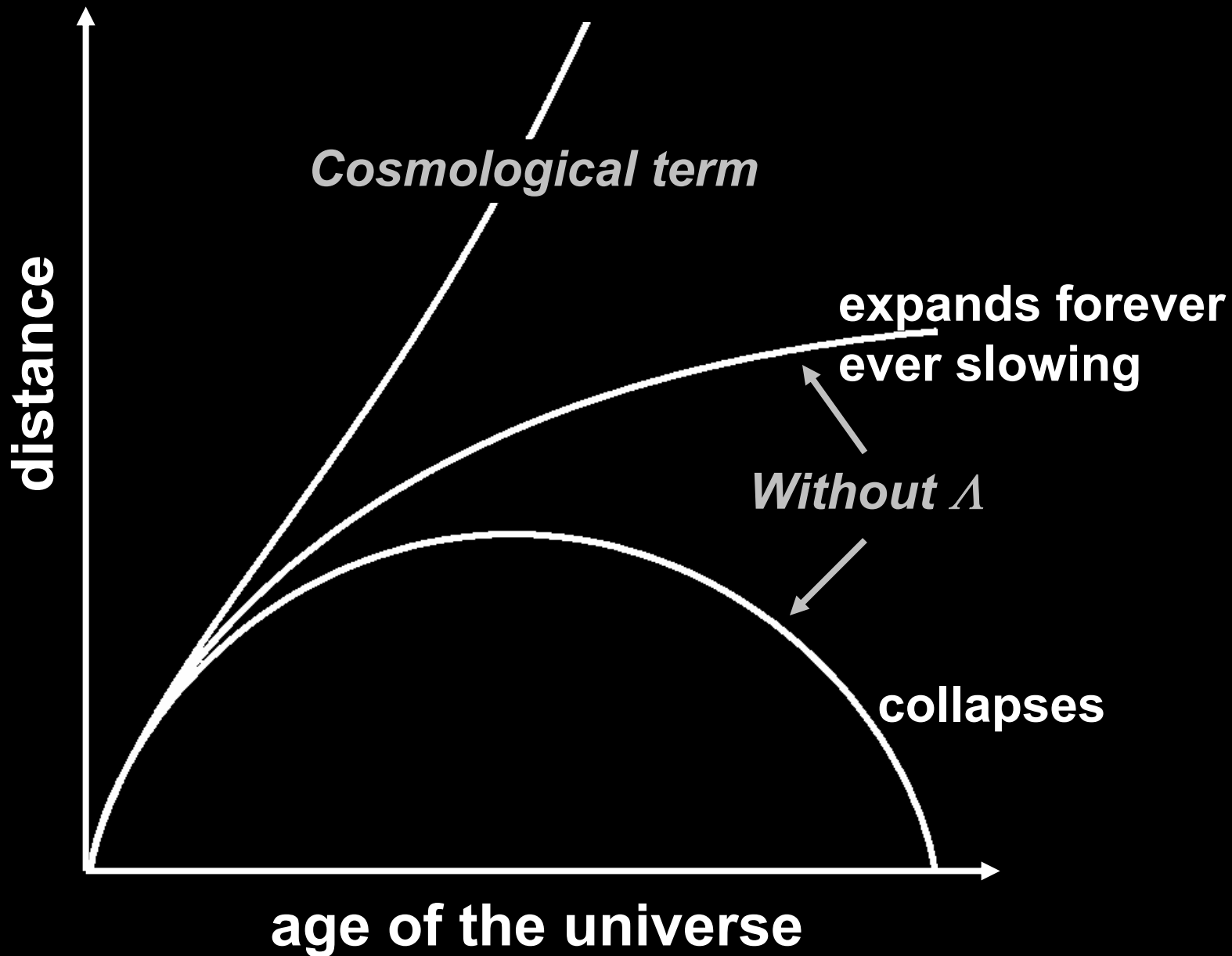
1929 Hubble discovered expansion of the Universe.

1934 Einstein called it “my biggest blunder.”

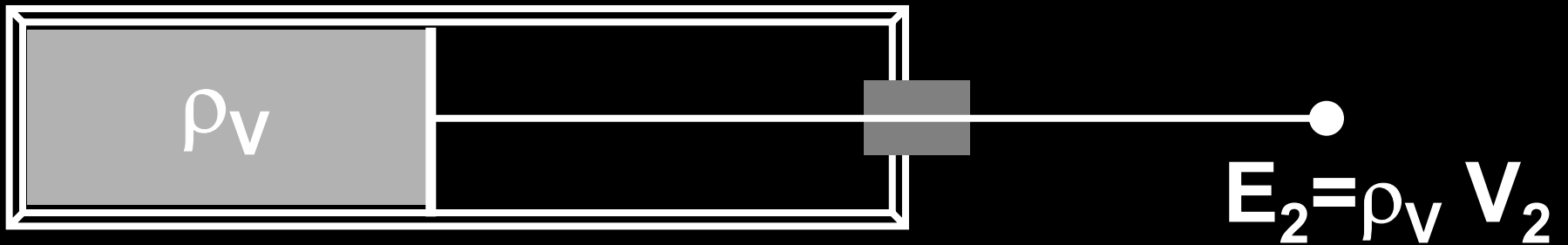
1998 Astronomers found evidence for it.



Our Cosmic Destiny

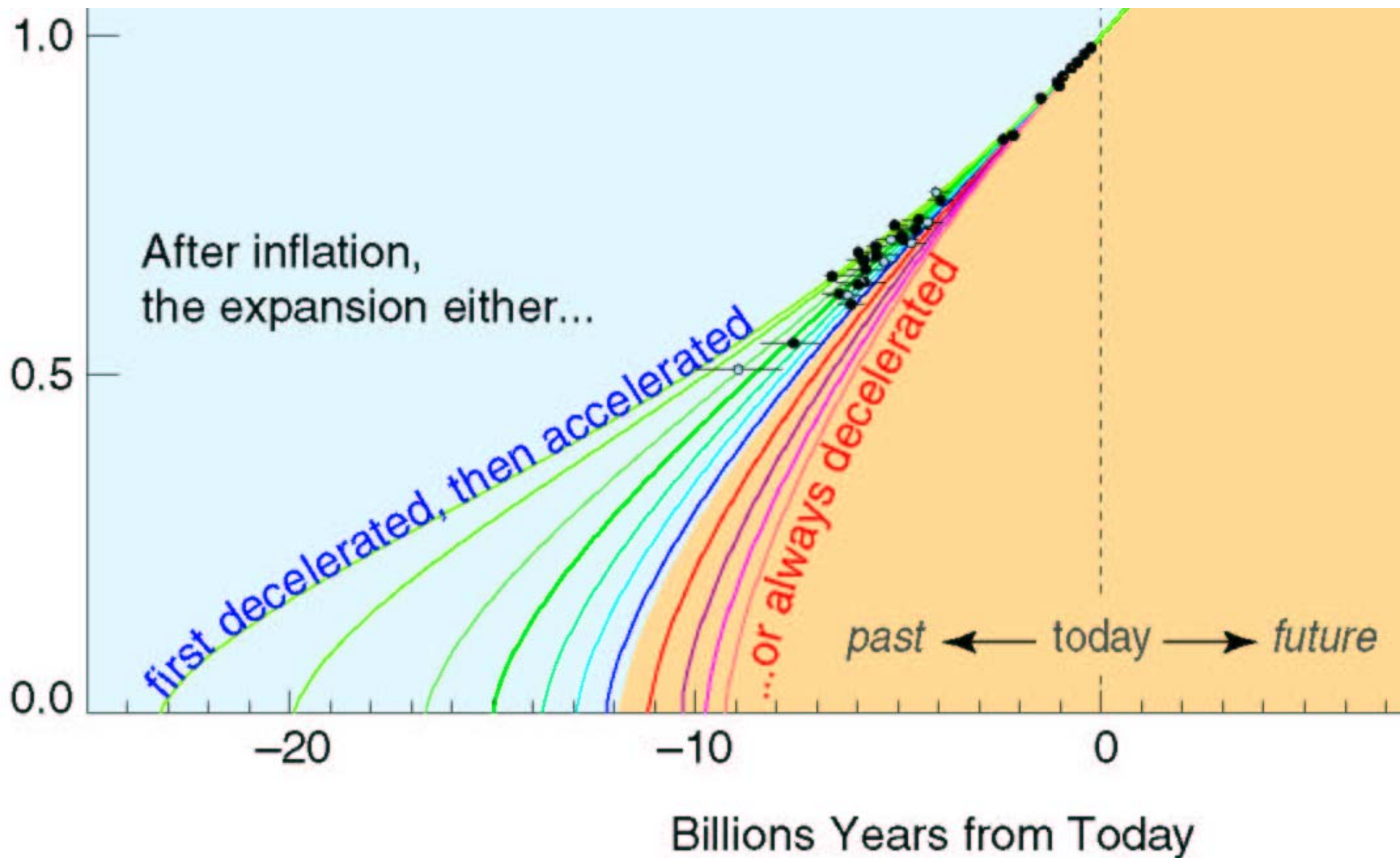


Vacuum pressure

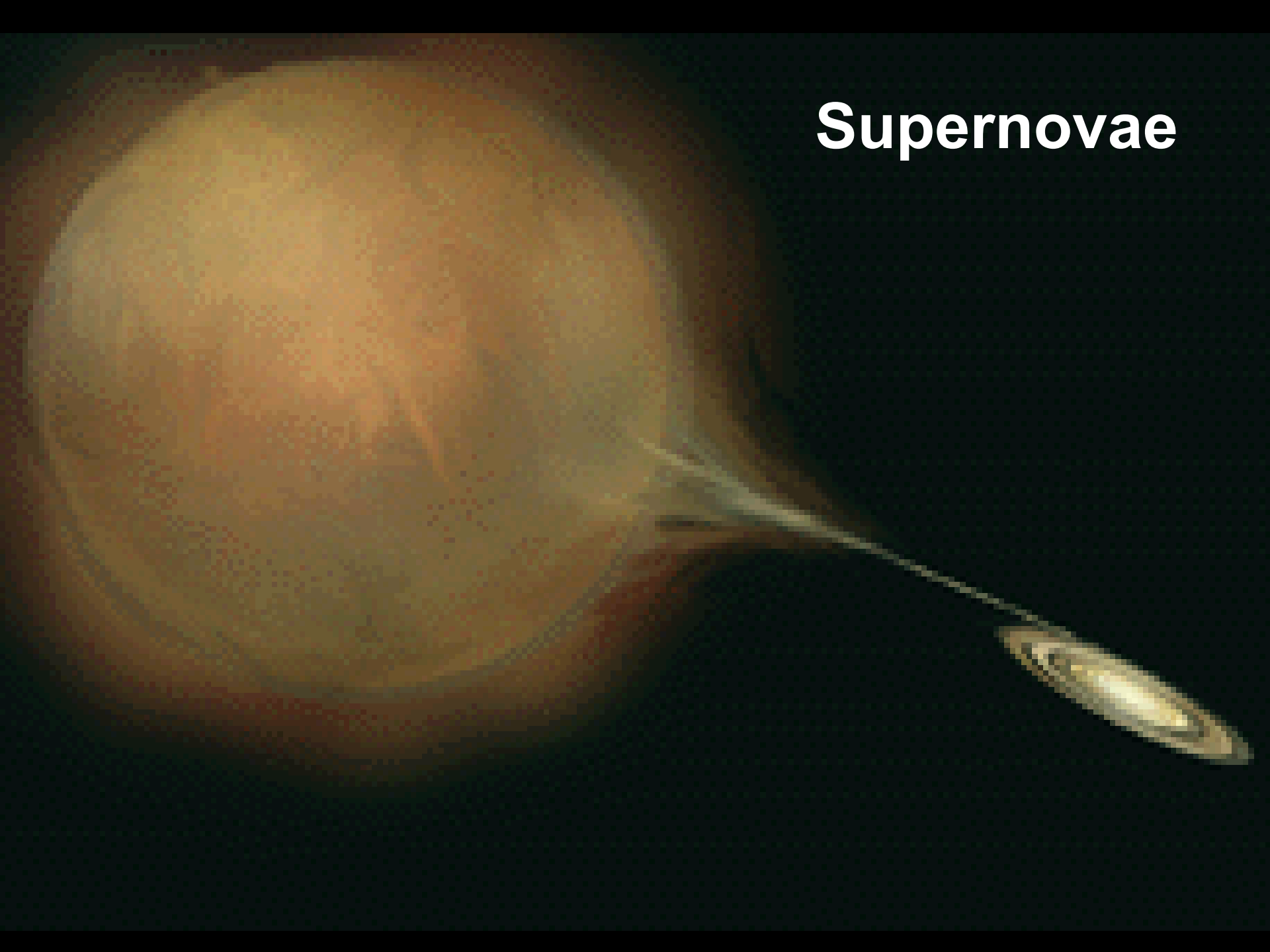


$$E_2 > E_1$$

had to pull piston
“negative pressure”



Supernovae

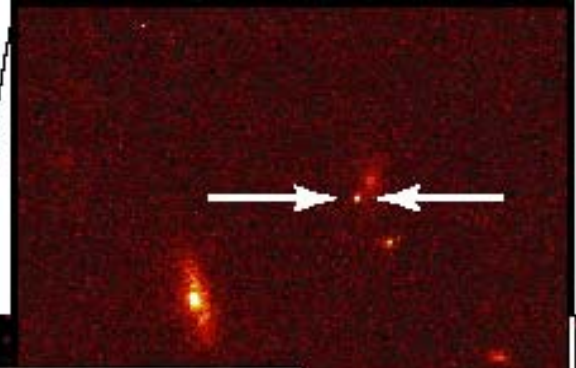


SN 1987A in the LMC

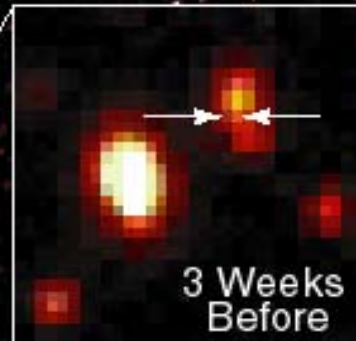
© Anglo-Australian Observatory



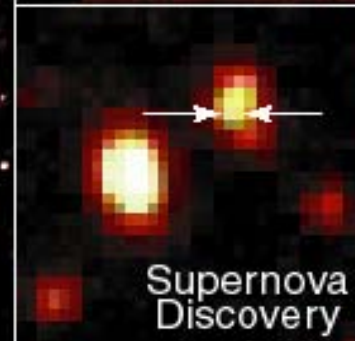
Supernova 1998ba
Supernova Cosmology Project
(Perlmutter, *et al.*, 1998)



(as seen from
Hubble Space
Telescope)

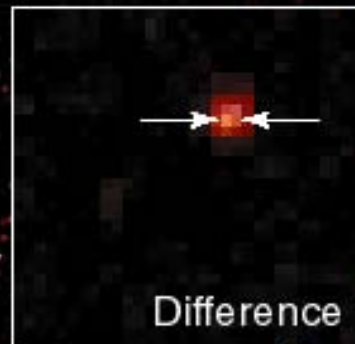


3 Weeks
Before

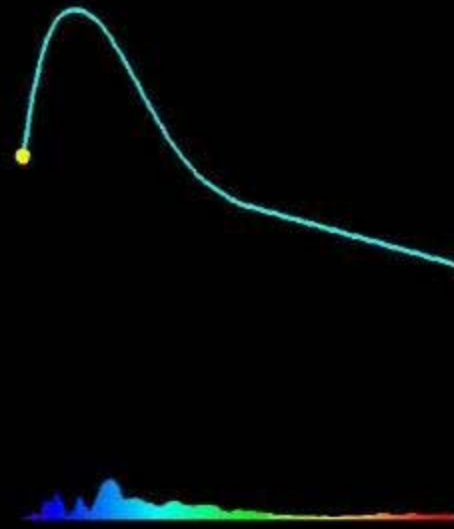


Supernova
Discovery

(as seen from
telescopes
on Earth)

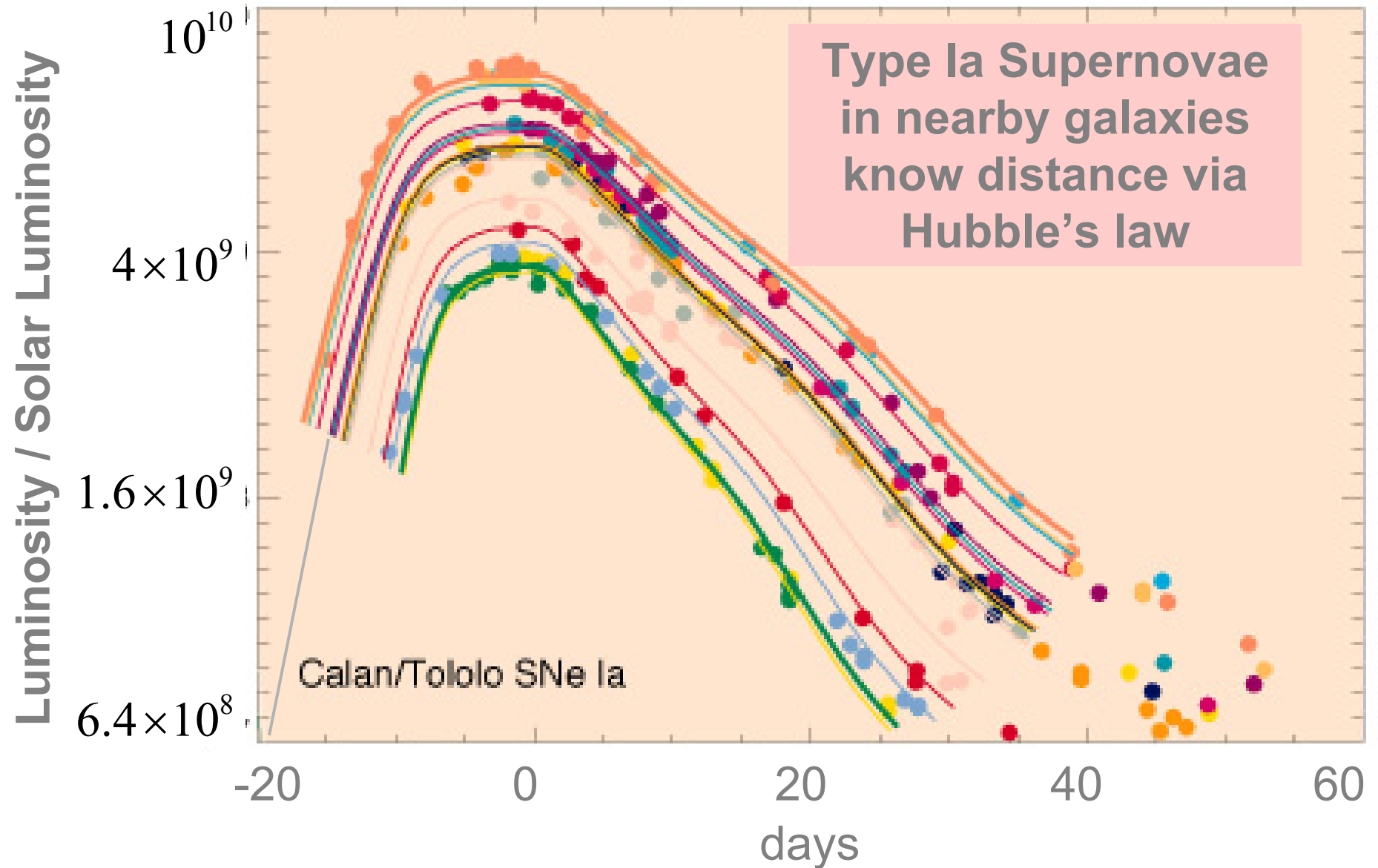


Difference

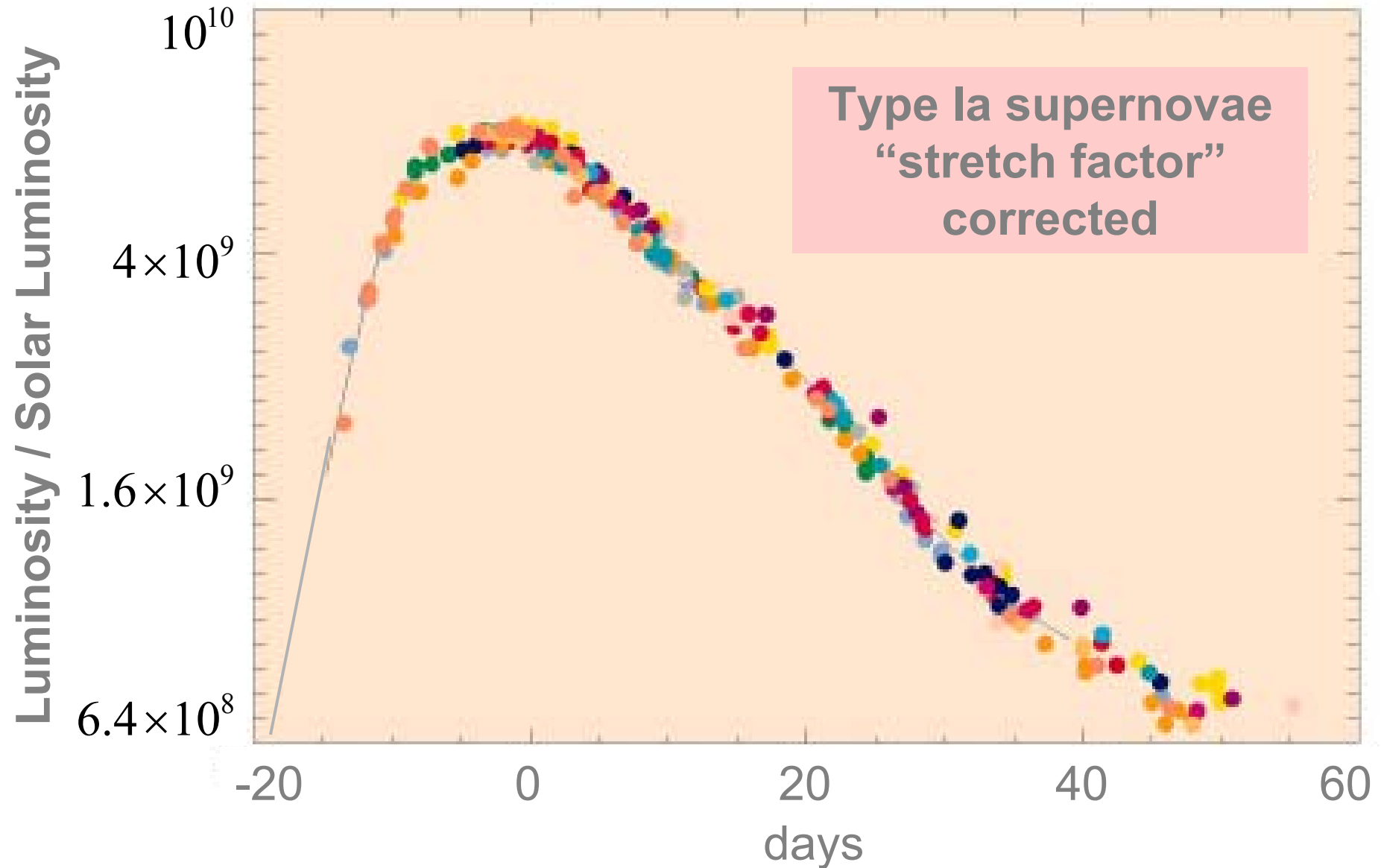


Centaurus A

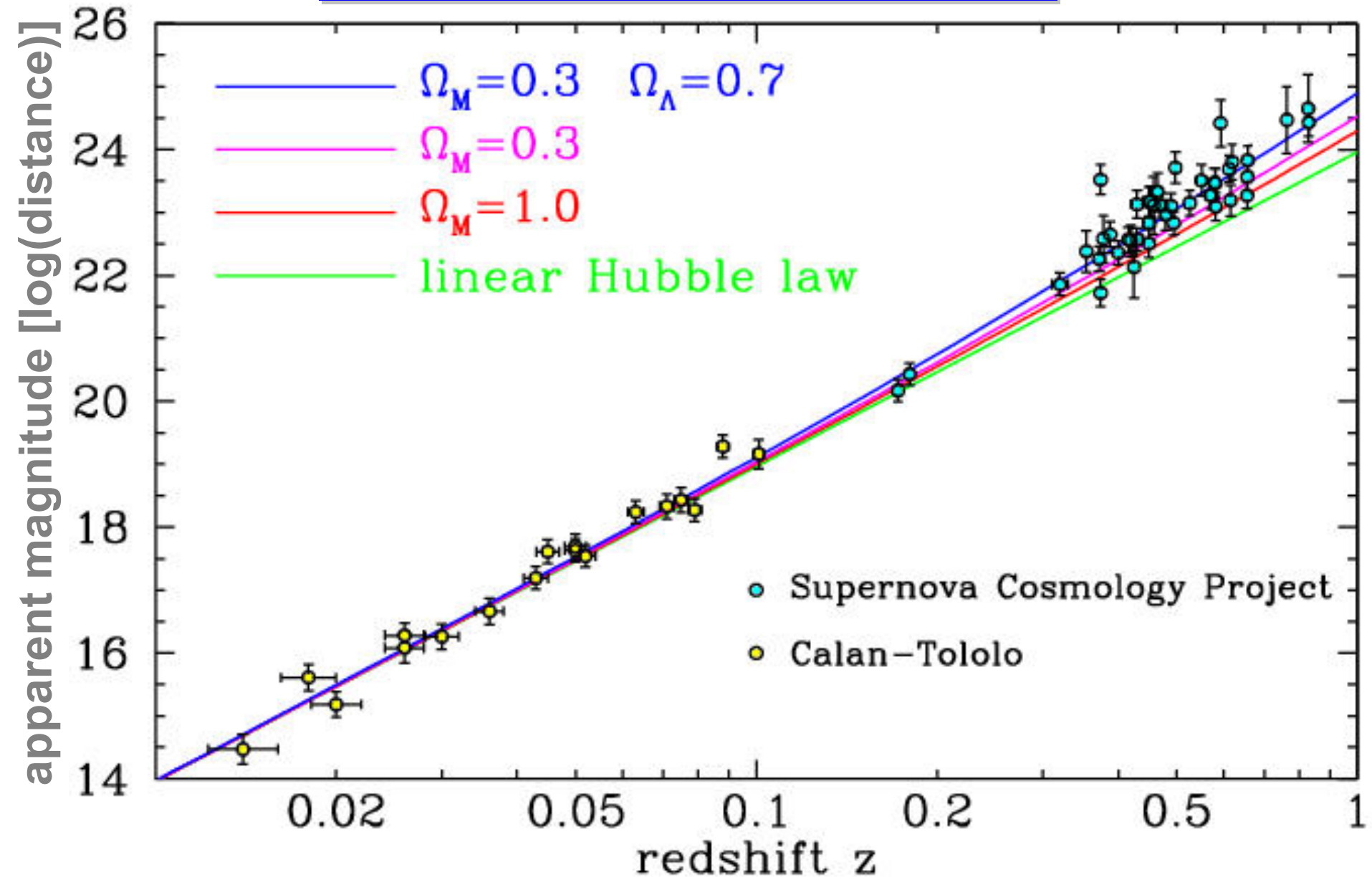
Type Ia supernova are standard candles



Type Ia supernova are standard candles



Type Ia supernova



Cosmological constant ***(Dark energy)***

Mass density of space: $10^{-30} \text{ g cm}^{-3}$

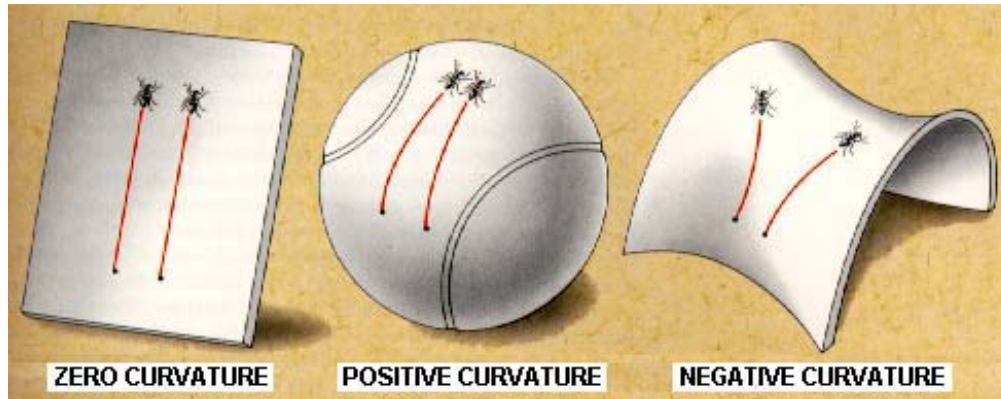
The unbearable lightness of nothing!

Cosmo-illogical constant?

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

Geometry = Matter

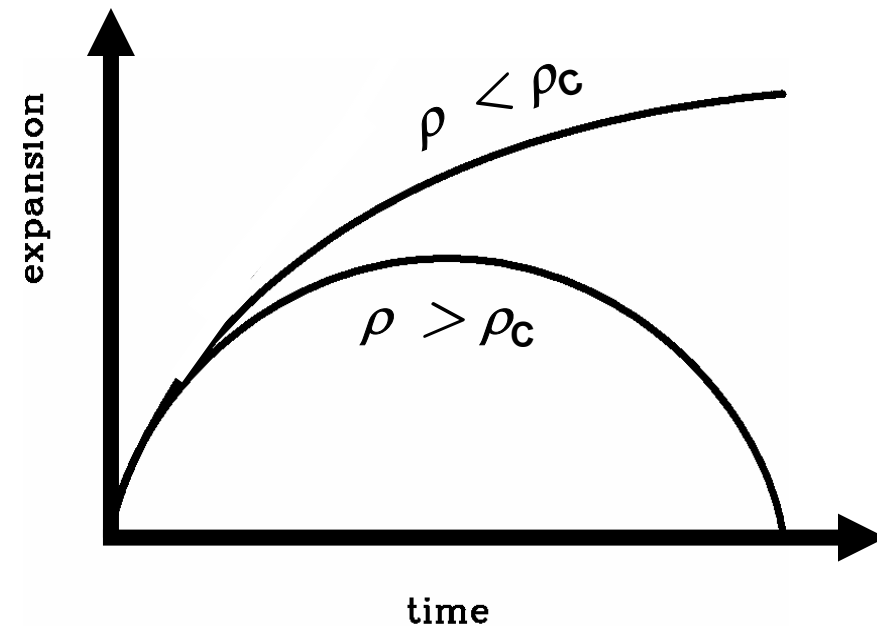
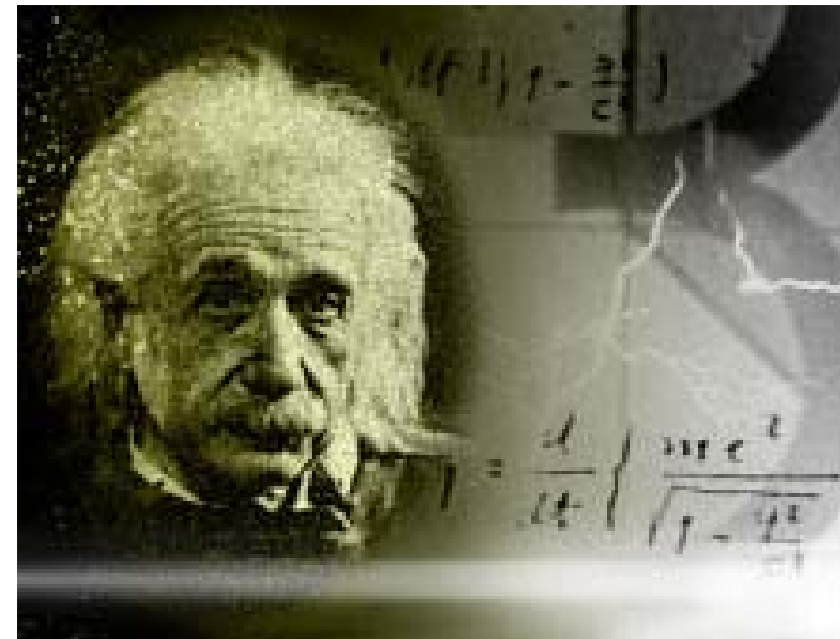
Curvature = Matter



$$\rho = \rho_c$$

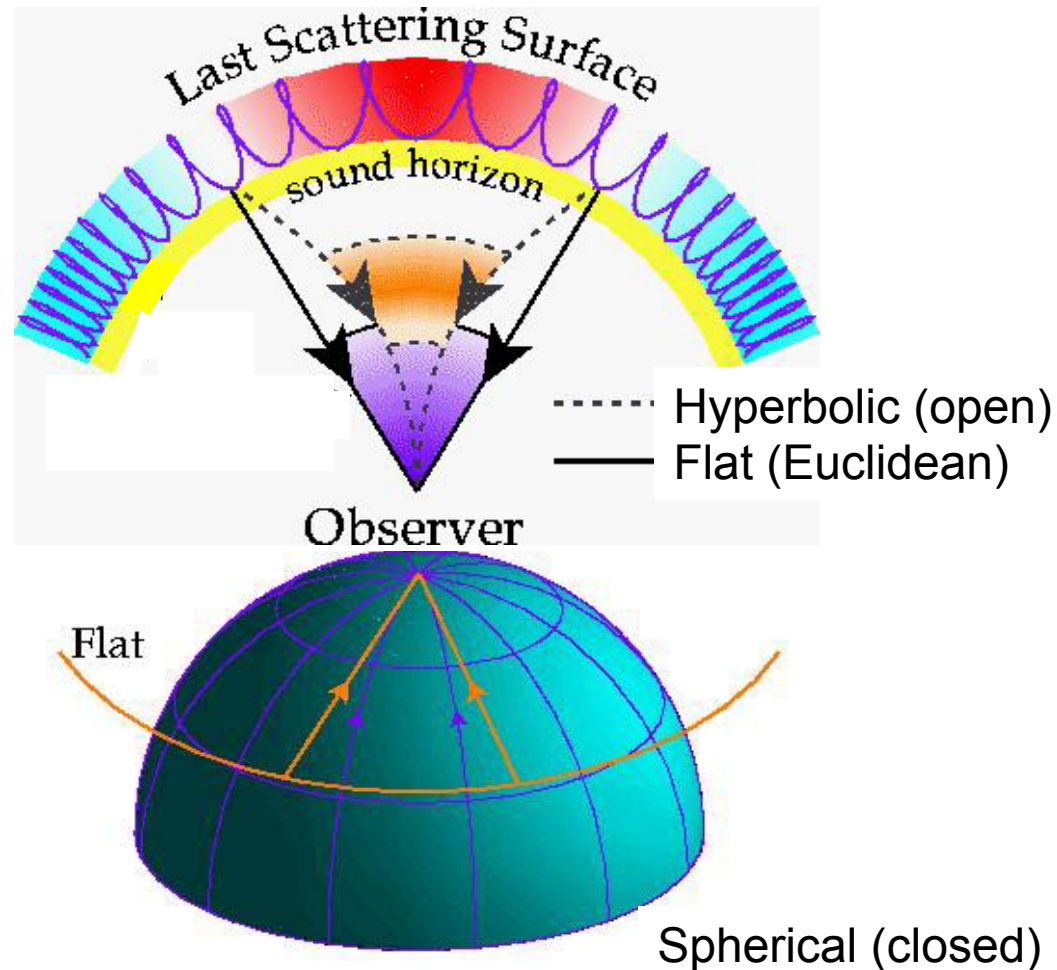
$$\rho > \rho_c$$

$$\rho < \rho_c$$

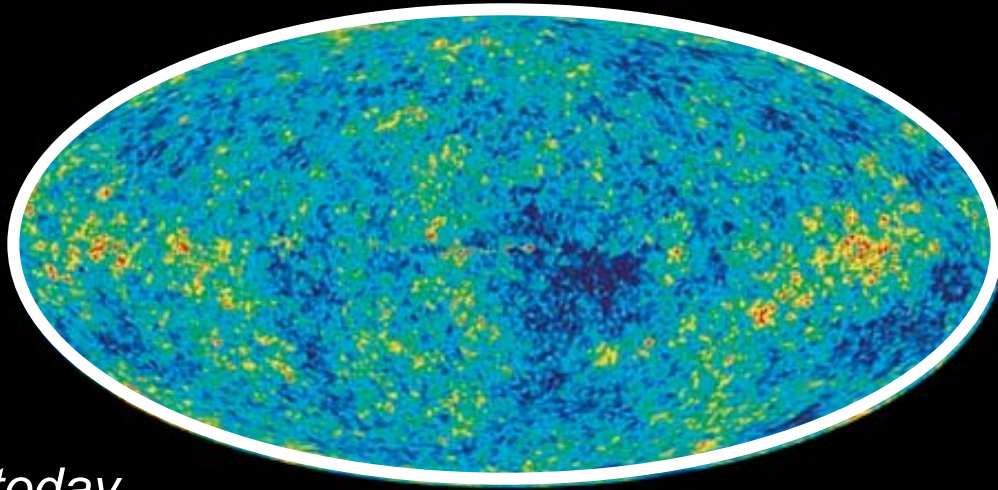


The sound horizon

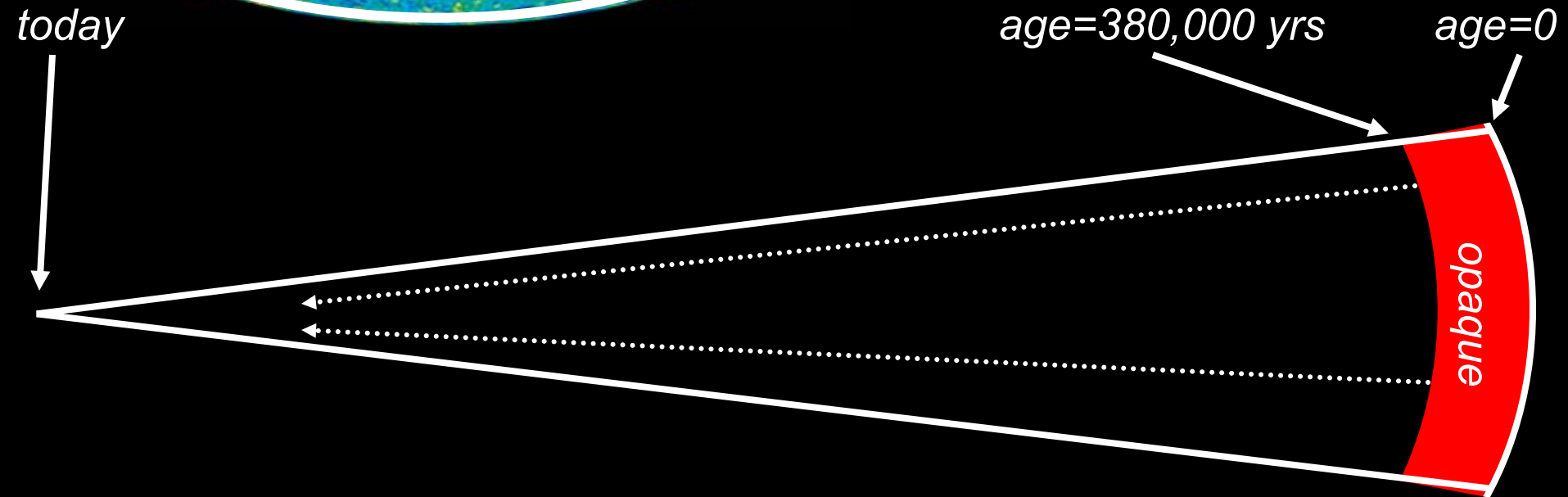
Sound travel distance known



Looking out in space is looking back in time.



**CBR: a snapshot of the
universe 380,000 AB**



$$\Omega_{TOTAL} = 1$$

$$\Omega_{MATTER} = 0.3$$

$$1 - 0.3 = 0.7$$

The Cosmic Food Chain

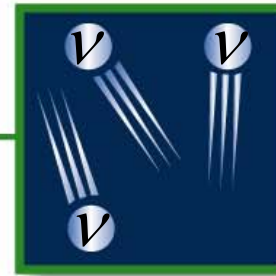
Radiation:	0.02%
Heavy elements	0.03%
Neutrinos	0.47%
Visible matter:	0.50%
Dark H & He	3.98%
Dark matter:	25%
Dark energy:	70%

Cosmic Pie

Radiation: 0.02%



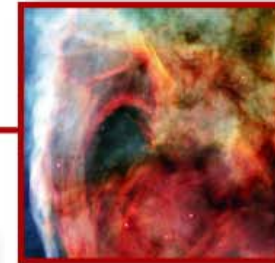
Chemical Elements:
(other than H & He) 0.03%



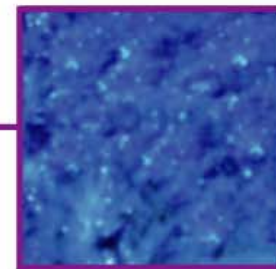
Neutrinos:
0.47%



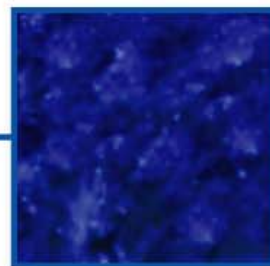
Stars:
0.5%



Free H
& He:
4%

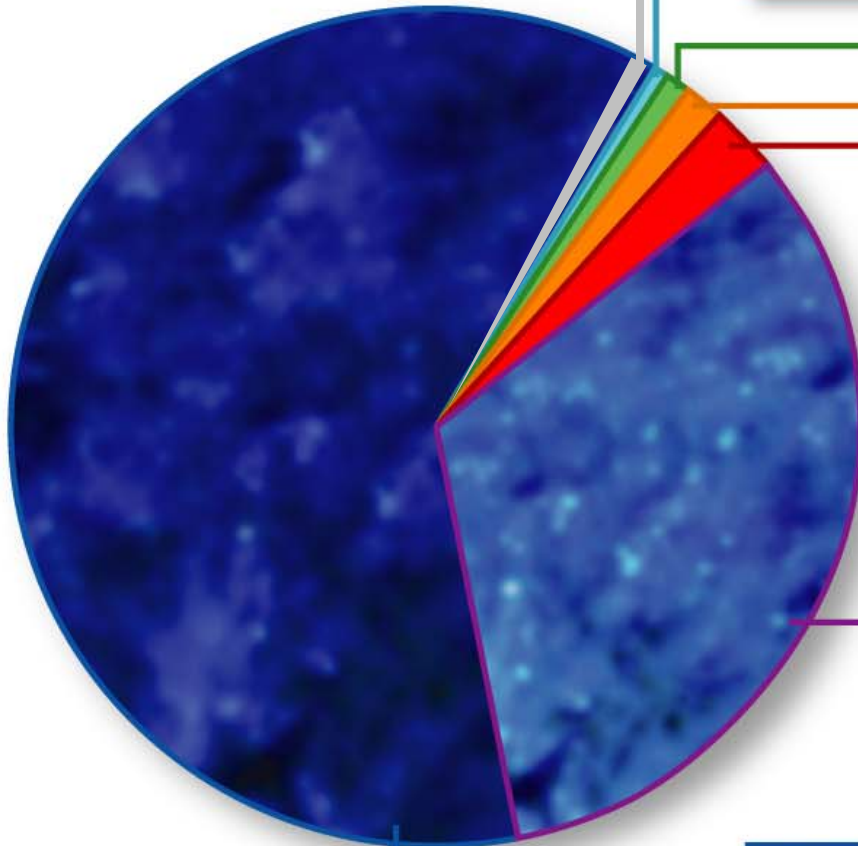


Dark Matter:
25%



Dark Energy:
70%

***Nothing
matters!***



Much ado about nothing
(the quantum vacuum)

NOTHING matters!

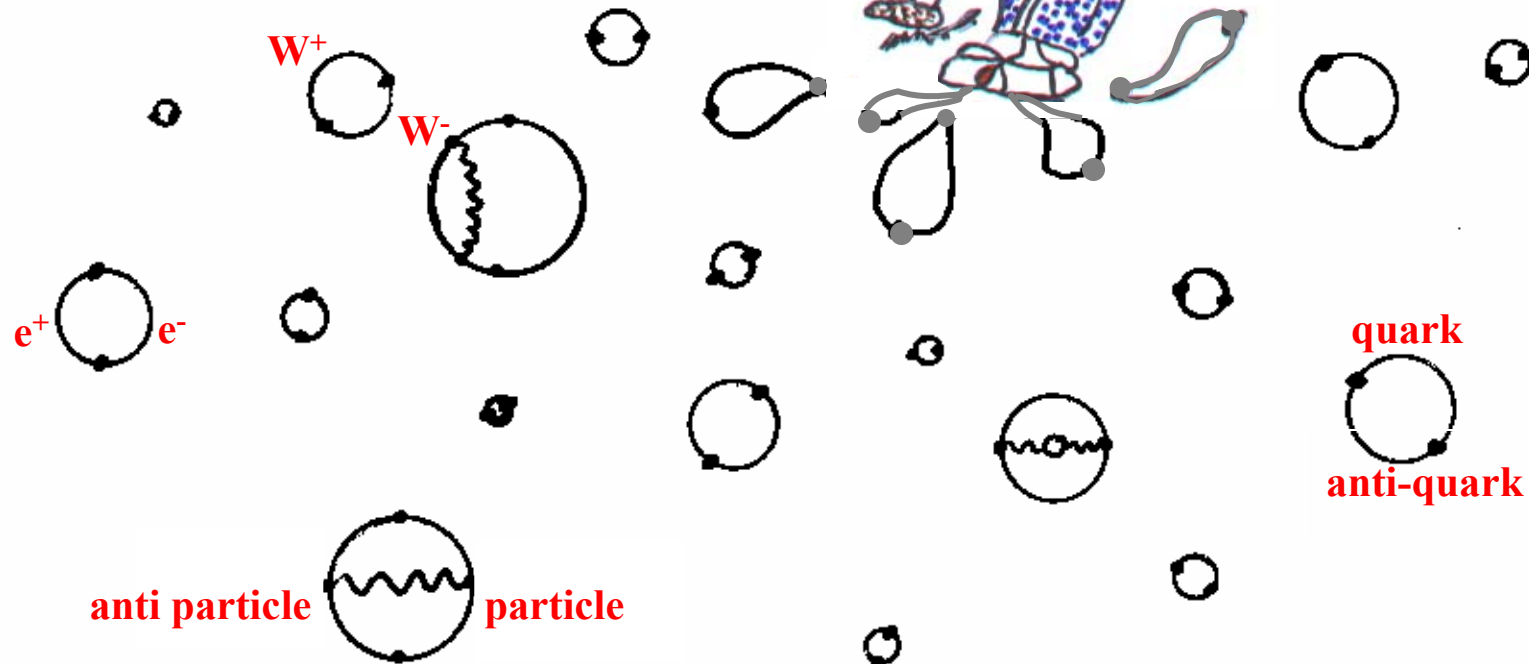
NOTHING is something!

NOTHING has energy!

NOTHING changes!

Uncertainty in the

Quantum Vacuum



Nothing is something!

Energy of the quantum vacuum

Observed: $\rho \leq 10^{-30} \text{ g cm}^{-3}$

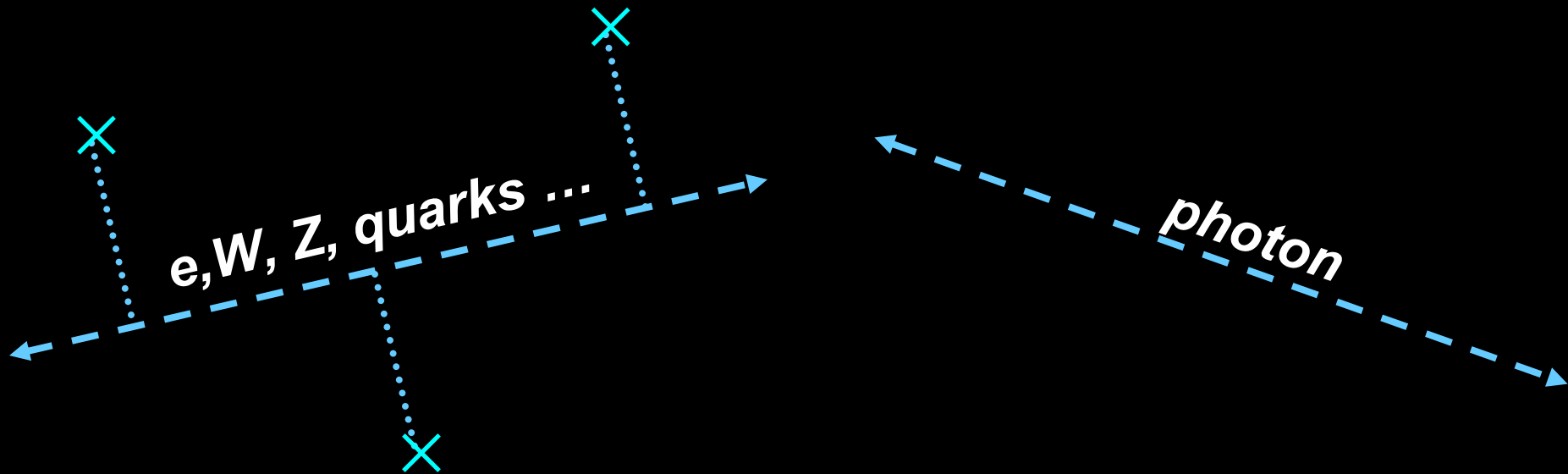
Quantum field theory: $\rho = \infty \text{ g cm}^{-3}$

Quantum gravity: $\rho = 10^{+90} \text{ g cm}^{-3}$

Supersymmetry: $\rho \leq 10^{+30} \text{ g cm}^{-3}$

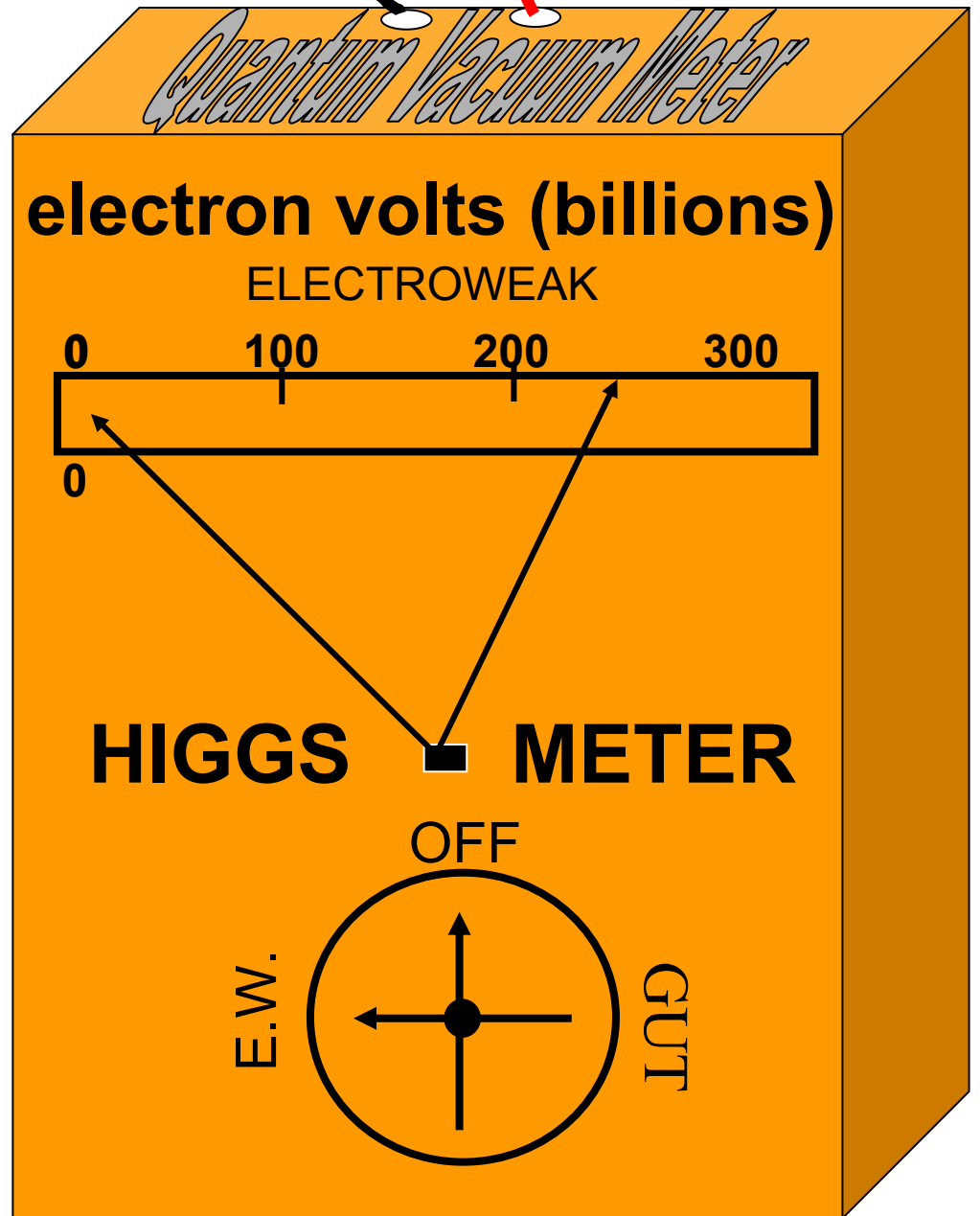
The Higgs potential

- The quantum vacuum has a Higgs potential
- Higgs field potential gives mass to quanta like quarks and electrons.





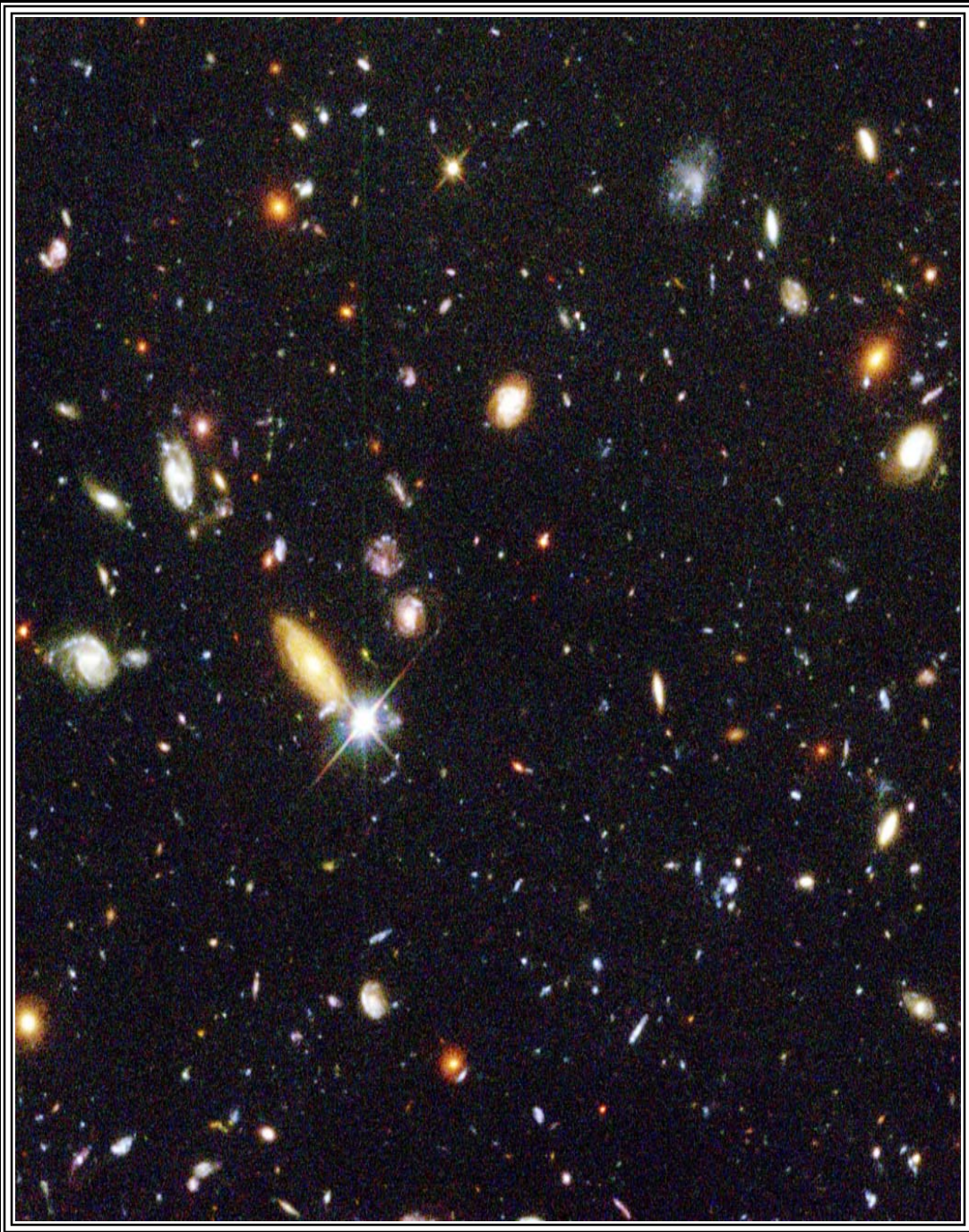
Prof. Peter Higgs



Nothing
has energy!

Energy of the quantum vacuum

Observed:	$\rho \leq 10^{-30}$	g cm^{-3}
Quantum field theory:	$\rho = \infty$	g cm^{-3}
Quantum gravity:	$\rho = 10^{+90}$	g cm^{-3}
Supersymmetry:	$\rho \leq 10^{+30}$	g cm^{-3}
Higgs potential:	$\rho \sim -10^{+25}$	g cm^{-3}
Other sources:	$\rho \sim \pm 10^{+20}$	g cm^{-3}

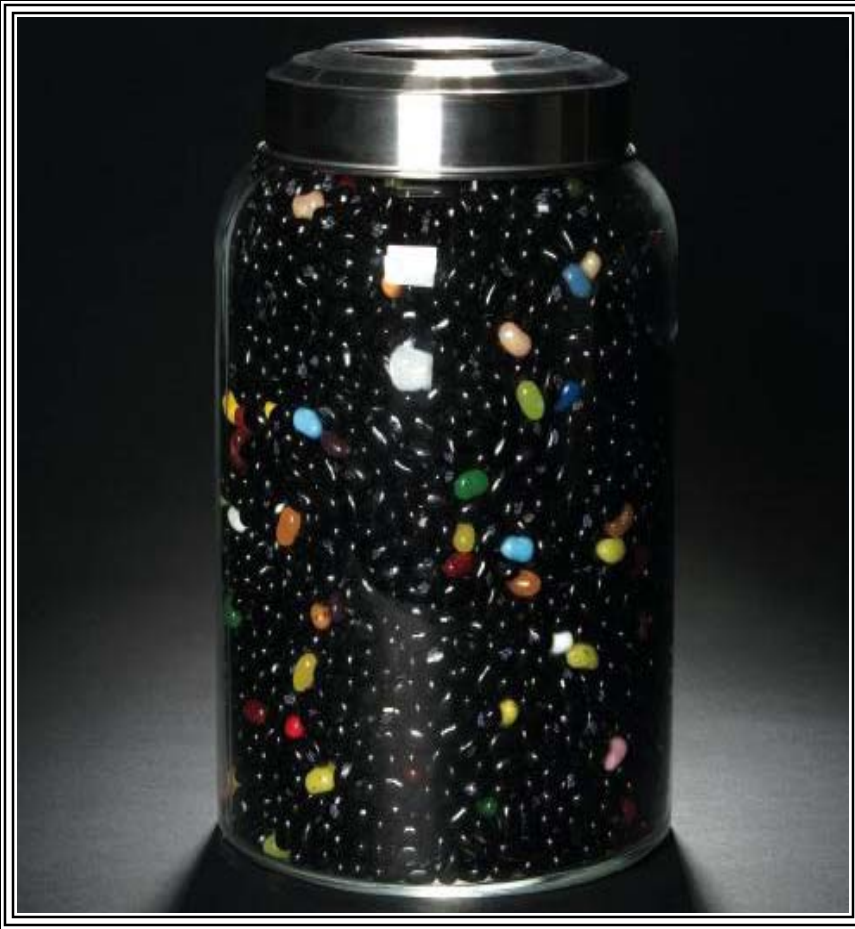


**“To me every hour of
the light and dark is
a miracle. Every
cubic inch of space
is a miracle.”**

– Walt Whitman

- cosmic radiation**
- virtual particles**
- Higgs potential**
- dark matter**
- dark energy**

The Dark Side of the Universe



**95% of the
Universe Is Dark!**

Dark energy (and Dark Matter)



**Beware the
Dark Side**